CHARACTERISTICS OF FLOW INDUCED VIBRATIONS OF A VERTICAL LIFT GATE

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by
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CERTIFICATE

It is certified that the work contained in this thesis entitled **"CHARACTERISTICS OF FLOW INDUCED VIBRATIONS OF A VERTICAL LIFT GATE"**, by **SANJAY KUMAR SRIVASTAVA**, has been carried out under our supervision and that this work has not been submitted elsewhere for a degree.

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D E D I C A T I O N

I RESPECTFULLY DEDICATED THIS DISSERTATION

TO

MY PARENTS

SATISH CHANDRA SRIVASTAVA

AND

PREMVATI SRIVASTAVA

FOR ALL THE LOVE, SUPPORT AND UNDERSTANDING

THEY HAVE GIVEN TO ME THROUGHOUT MY LIFE

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ABSTRACT

Experience shows that a vertical lift gate with a flat bottom exhibits strong flow induced vibrations and that there is an interaction between the vibration of the solid boundaries and the exciting force but the nature of these vibrations and of the exciting force have not been studied in detail, moreover, the interrelationship between exciting force, flow pattern, and vibration amplitude have also not been set up in general form.

This thesis, based on extensive experimental work, presents the result of an investigation of interrelationship of dynamic force and oscillations of a vertical lift gate submerged under free surface flow. The primary aim of this work is to develop a methodology for separate measurement of exciting forces, acceleration, and displacement and to correlate the gap ratio with the amplitude of vibrations. The main parameters governing flow induced vibrations are gate geometry, gap ratio, upstream water depth, downstream water depth, mass, damping, and stiffness characteristics of the gate.

The experiments were conducted in an open water flume where the aforesaid parameters were measured with the help of

transducers. The signals so measured were amplified by a charge amplifier and stored in oscilloscope. The spectral analysis of the excitation force and gate response signal was conducted using the FFT algorithm. The normalized power spectra for the force on a rigid gate and the response of an elastic gate throw light on the nature of vibrations of a vertical lift gate. The critical vibration were observed near gap ratio 0.65 with downstream water depth equal to gate thickness.

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LIST OF NOTATIONS

The following notations are used in this thesis.

b = viscous damping coefficient

b_c = critical damping coefficient

C = linear spring coefficient

d = gate thickness

E = modulus of elasticity

f = dominant vibration frequency

f_n = natural frequency (in air)

F = net fluid force on vibrating gate

F_b' = out-of-phase component of F

F_m' = in phase component of F

F_m = gate mass force component

F_s = fluid-force on stationary gate

F_R = resultant fluid force component

F_r = Froude number

g = acceleration due to gravity

C_F = fluid force coefficient

C_{Fm} = in-phase force coefficient

C_{Fb} = out-of-phase force coefficient

C_m = in-flow added mass coefficient

h_1 = upstream water depth

h_2 = downstream water depth

I = moment of inertia

k_s = submergence depth over gate bottom at Vena Contracta

l = unsupported length of elastic support

m = stRuctural mass

m_r = structural mass ratio

Q = discharge in flume

Re = Reynolds number

s = gap ratio

S = power-density function

$S*$ = normalized power density function

t = time

t_r = dimensionless time

Tu = turbulence intensity

V = efflux velocity at Vena Contracta

V_r = reduced velocity

y = gate displacement amplitude

Y = relative gate displacement amplitude

β = damping ratio

φ = phase angle between F_R and y

ϕ = phase angle between F and y

ω = angular frequency

σ = root mean square value

ν = kinematic viscosity of the fluid.

CHAPTER I

INTRODUCTION

The flow of fluids around structures can cause destructive vibrations as well as useful ones. The flow induced vibrations have become increasingly important in recent years because of its great importance in structural design. The objective of designer is to control the vibrations when it is objectionable and to enhance the vibrations when it is useful. Objectionable vibration in a structure may cause eventual failure.

One of the most dangerous vibrations of hydraulic gates with overflow and underflow is flow induced vibrations. The gate is a nonlinear system which transforms aperiodic input into a different aperiodic output.

There is a lot of data available on flow induced vibrations of hydraulic control gates. However, we can not explain the mechanism behind the excitation of self sustained gate vibrations because of a great diversity of practical gate geometries, boundary conditions and complex nature of the dynamic interactions between the flow and the structure.

The present thesis is limited to the dynamic behavior of planar under flow type gates with a flat underside in free surface flow having one degree of freedom in the vertical direction. This simple configuration has been deliberately chosen in order to eliminate various secondary effects due to other boundary and flow conditions that may obscure the basic excitation mechanism of a rectangular gate.

In parallel with Naudascher, E. et. al., works on vortex excited vibrations of an underflow gate in 1986, the present thesis is an experimental study of the excitation and elastic response of such a gate that is free to vibrate in vertical direction.

The details are presented in the following chapters . Chapter II contains a review of the literature .References mainly contain the works of Naudascher, Blevins, Campbell, Abelev and Hardwick . In chapter III, a dimensional analysis is carried out for the gate vibration problem. In chapter IV the description of the experimental setup along with the instrumentation used is presented. Results and conclusions are presented in chapter V & VI, respectively. Measured signals for various gate openings are presented in Appendix - A . Appendix - B and Appendix - C contain information on data acquisition, signal processing and spectral analysis.

CHAPTER II

LITERATURE REVIEW

2.1 BACKGROUND AND AIMS OF THE STUDY

Most of the flow induced-vibrations can be traced to the instability of the flow itself. Whatever be the nature of the in stability, its effect in combination with disturbances will lead to development of fluctuations of velocity and pressure in an initially steady flow, unless the Reynolds number of flow is so small that viscous effects are large enough to damp this process. Depending upon the strength of mechanism by which (i) the intensity of these fluctuation get amplified, (ii) their correlation in space increases, and (iii) the distribution of their energy becomes concentrated around a dominant frequency, an effective force fluctuation along the flow boundaries may result and quite possibly lead to structural vibrations.

Muller was the first person who investigated the weir gate vibration. Hydraulic gates may be subjected to various modes of self excited vibrations differing in their physical nature and onset conditions. The mechanism of excitation of these vibrations is governed mainly by the

character of the nonstationary hydrodynamic forces dependent on the motion of the gate on flow. According to Abelev S.A., [1] we assume that this excited vibration of the gates may be divided into two basic categories :

(a) Vibration due to vorticity associated with the separation of the flow from the lower lip of the gate when the eddy formation in the water past the gate is synchronized with and controlled by the structural vibrations (the eddy mechanism of the excitation).

(b) Vibrations which may occur at high velocity of the jet flow oriented along the vertical surface of the gate (the jet flow mechanism).

According to later references [10] flow induced vibrations may be classified into (i) Extraneously-Induced Excitation, caused by a pulsation in flow or pressure which is not an intrinsic part of the vibrating system, (ii) Instability-induced excitation, brought about by flow instability, and (iii) Movement-Induced Excitation, due to exciting forces which arise from the movement of a body within the vibrating system.

When a free shear layer lies close to a stationary solid boundary, such that the velocity field of eddies induce intermittent reattachment of the separated flow to the

boundary. Locher [9] has shown for this case that the fluctuating flow pattern exerts a pulsating force with a well defined frequency on boundary.

Kolkman [8], Campbell [4], and Pertrikat [12] extended these studies and observed the strong vibrations of submerged gates with small openings. They came to the conclusion that the vibrations were self controlled and originated from the interaction between the unstable shear layer separating from the leading edge of the gate bottom and the elastic gate.

Hardwick D.J., [6] studied the vibrations of the solid boundaries and their exciting force in detail. In his experimental work of excitation and gate response of one which is free to vibrate in the vertical direction, he measured the dynamic net force acting on the gate bottom and the vertical gate displacement. Hardwick established an interrelationship between the exciting force, flow pattern and vibration amplitude in a nonlinear amplitude response curve. However, no spectral information of vibration characteristics was given.

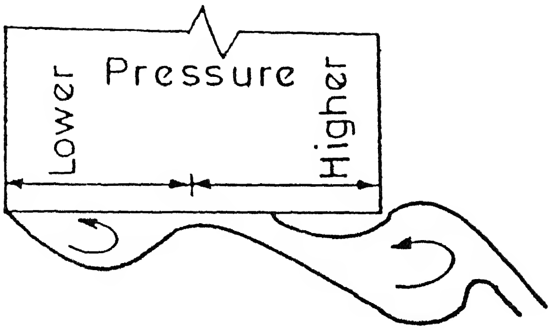
Shyam Sunder [14] studied the gate vibrations using a strain gauge bridge for measuring the deflection of the elastic cantilever to which the gate was connected. As the strain gauge bridge was calibrated by static loading, the strain gauge bridge output was proportional to the force

acting on the gate as well as displacement of the gate.Naudascher,et. al., [11] made a comprehensive study of the gate vibration problem. Spectral analysis of excitation force and the gate response was performed with Fourier Analyzer (HP 5451 C) for measuring duration of over 20 seconds. The results were plotted in the form of normalized force and the response auto-power spectra.

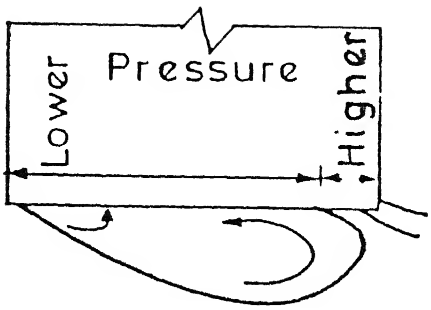
The main aim of the present study is to develop a methodology for signal measurement and spectral analysis by FFT program on HP main frame computer instead of using a Fourier Analyzer. The present experimental study also includes the separate measurement of the exciting force, vertical displacement of the gate, and acceleration. The normalized power density function (with the help of FFT program) of the above forces has been found out for both elastic and rigid gate case.

2.2 ORIGIN OF EXCITING FORCE

In the present study the flow pattern was correlated with oscillatory motion of the gate with precision. The vorticity of the free shear layer becomes concentrated in the growing disturbance as a new eddy beneath the upstream third of the gate bottom.



(a) Maximum upward force (gate rising)



(b) Maximum downward force (gate falling)

FIG. 2.1 FLOW PATTERN RELATED TO EXCITING FORCE

In the absence of the instantaneous pressure distribution on the bottom of the gate some idea of the variation of force can be had from consideration of a theoretical model of a vortex and its image in a steady flow [6]. The unsteady flow has been represented elsewhere by a series of steady states, with the growth of circulation of each member of the vortex pair equated to the estimated circulation in the free shear layer. The dimension of the vortex must increase if the vortex is to remain stable in flow, and this growth corresponds to the expansion of the eddy. The expansion is more rapid as the velocity of the jet V_j beneath the gate increases. The pressure distribution is shown in fig. 2.1. In the fig. 2.1(a) the higher velocity of the new eddy gives rise to locally lower pressure on the bottom of the gate. Downstream of the new eddy where the velocity is lower, the pressure rises to higher value of the tail water zone. The maximum upward force is thus applied when the new eddy is still small and the old eddy has been shed downstream. The gate rises in response to the applied force. In fig. 2.1(b) the maximum of downstream force is applied when the eddy is large and the zone of reattachment is small and the gate starts to fall. By repetition of rising and falling motion of the gate, it starts vibrating.

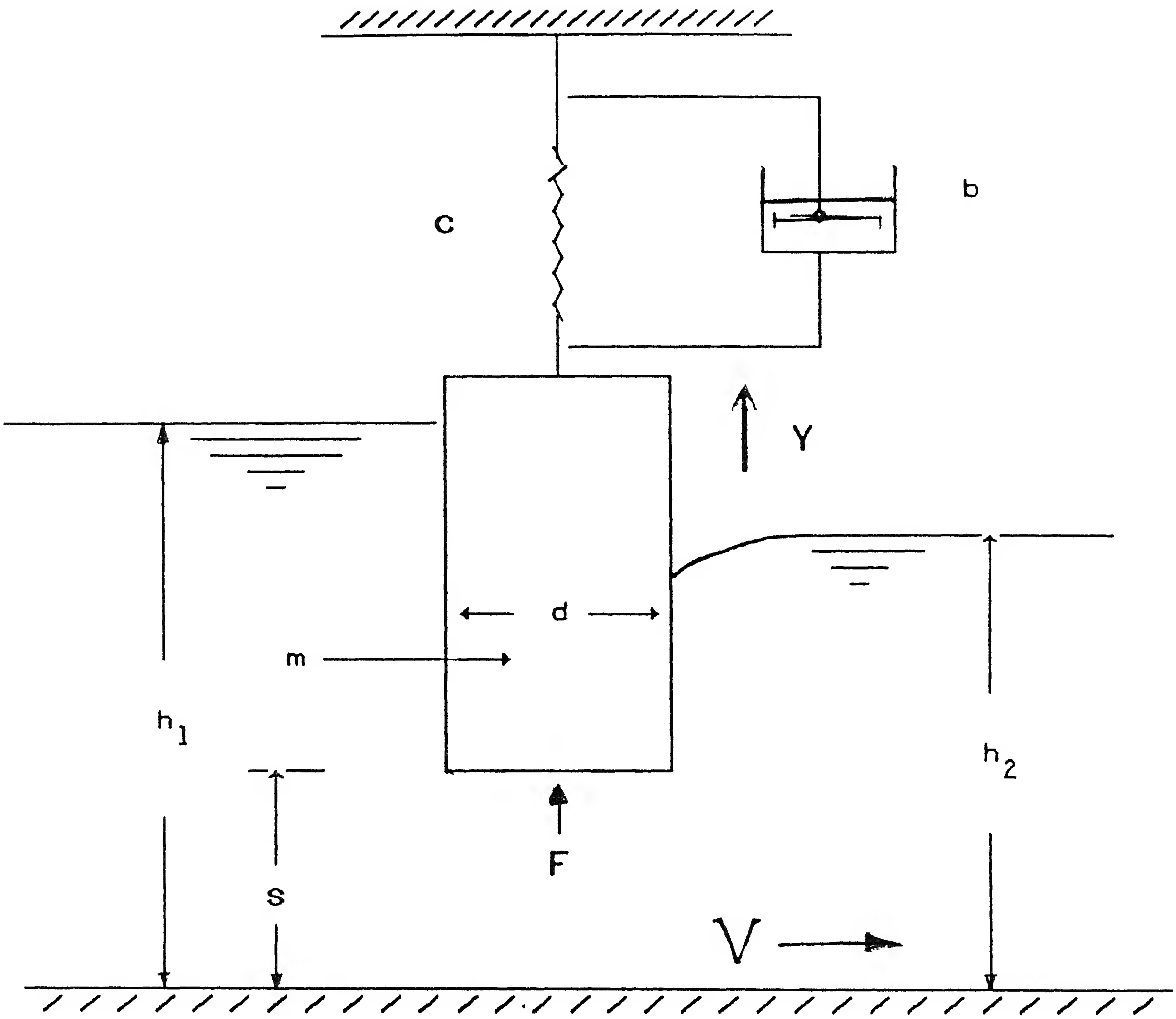


FIG. 3.1 DEFINITION SKETCH

CHAPTER - III

DIMENSIONAL-ANALYSIS

The following discussion is based upon similitude analysis of Thang and Naudascher [11] The equation for model in fig 3.1 is a second order linear ordinary differential equation with constant coefficients.

$$m \ddot{y} + b \dot{y} + c y = F(t) \quad .... \quad ...(1)$$

Here m, b and c denote the structural mass, damping and stiffness (in air), respectively. y and its two derivatives $\dot{y}$ and $\ddot{y}$ denote the displacement, velocity, and acceleration of vertical gate and F(t) is the fluctuating component of the fluid force in the vertical direction acting on the gate bottom.

The above equation may be rewritten in a more convenient form by defining,

$$c / m = \omega n^2 \quad \text{and} \quad b / m = 2 \zeta \omega n \quad \text{or} \quad \zeta = b / 2 \sqrt{c * m}$$

where ω_n $(=2\pi f_n)$ is the natural circular frequency of the system and ζ is called the damping factor. Since m, b and c are positive ζ is also a positive number.

$$\ddot{y} + 2\zeta\omega_n\dot{y} + \omega_n y^2 = F(t)$$

or,

$$\ddot{Y} + 2\beta\dot{Y} + \bar{Y} = C_F V_r^2 / 8\pi^2 m_r \quad ....(2)$$

The nondimensional variables that have been found to be useful in describing the vibration of an elastic structure in a subcritical (IF < 0.3) steady flow are,

(i) Geometry $(a/b, s/d, h_1/d, h_2/d)$

(ii) Reduced velocity ($V_r = V / f_n d$)

(iii) Damping ratio ($\beta = b / 2\omega_n m$)

(iv) Mass ratio ($m_r = m / \rho d^2 l$)

(v) Fluid force coeff. ($C_F = F / .5\rho V d^2 l$)

(vi) Reynolds number ($Re = Vd/\nu$ & Vs/ν)

The fluid flow and the structure are interactive system, and their interaction is dynamic. These systems are coupled by the force exerted on the structure by the fluid. Because of this coupling no linear solution is possible but the gate - displacement amplitude can be expressed in a general way as a function of three main groups of parameters as follows :

$$Yo = \text{Function (Boundary geometry, Fluid flow dynamics, System dynamics)}$$

$$= \text{Function } (s/d \ , \ h_1/d \ , \ h_2/d \ , \ Re \ , \ Tu \ , \ Vr \ , \beta \ , \ mr \ )$$

It is difficult to find an analytical expression for the relationship between Yo and these parameters. Vickery and Watkins assume a linear mechanical system and harmonic steady-state force and response function :

$$C_F = C_{Fo} \ \mathrm{Sin}\ \omega t$$

$$Y = Yo \ \mathrm{Sin}(\omega t - \phi)$$

$$Y = \frac{1}{4\pi} \frac{C_{Fb} \ V_r^2}{Ks} \frac{wn}{\omega} \qquad \ldots\ldots \quad \ldots\ldots \quad (3)$$

$$C_{Fb} = C_{Fo} \sin \phi$$

Here ϕ is the phase-lag angle, C_{Fb}, and Ks denotes out of the phase fluid force coefficient and mass damping coefficient and $\omega n/\omega$ is the ratio of natural frequency (in air) to vibration frequency (in water).

$$\frac{\omega n}{\omega} = \left[1 + \frac{Cm}{mr} \right]$$

Where $Cm = m/\rho d^2 l$ is the added mass coefficient. So equation (4) may be written as

$$Yo = \frac{1}{4\pi} \frac{C_{Fb} V_r^2}{K_r} \sqrt{1 + \frac{C_m}{m_r}}$$

In addition, Den Hartog, J.P. [5] provides flowing formula for natural frequency in still water and coefficient of critical damping.

$$\omega_n = \sqrt{\frac{k}{m}}$$

$$f_n = \frac{\omega_n}{2\pi}$$

f_n = natural frequency of the gate

m = mass of the system

k = spring constant of the system

$$= \frac{3EI}{l^3}$$

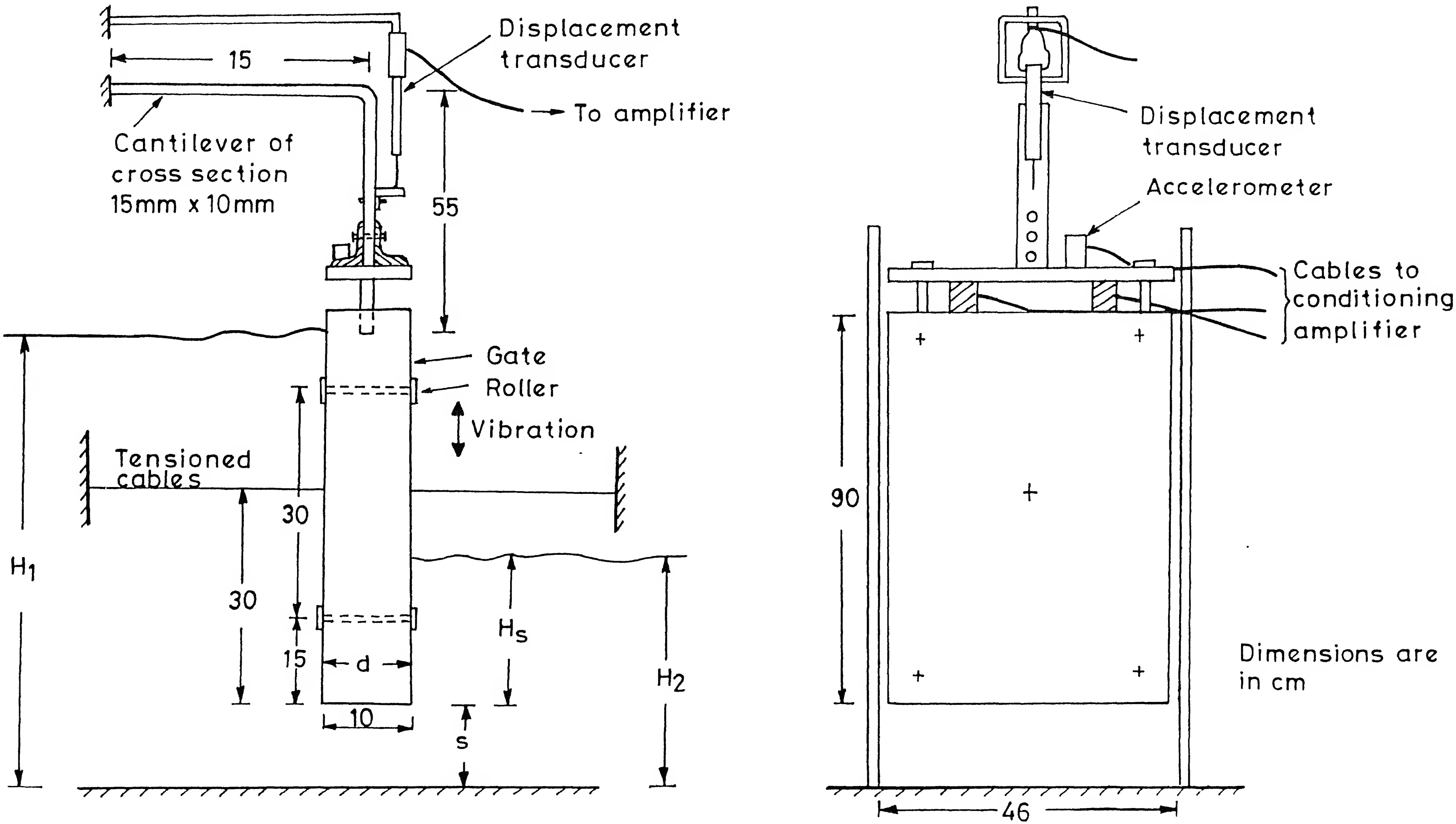
Here E = 70.0×10^9 N/m^2 for aluminium.

And critical damping coefficient (bc) = $2\pi\omega_n$

$$\frac{b}{b_c} = \frac{1}{2\pi}\left(\frac{X_n - X_{n+1}}{X_n}\right)$$

Where X_n = n th amplitude during the vibration

X_{n+1} = (n+1) th amplitude during the vibration



LONGITUDINAL SECTION OF GATE

END VIEW OF GATE

FIG.4.1 VORTEX EXCITED VERTICAL LIFT GATE

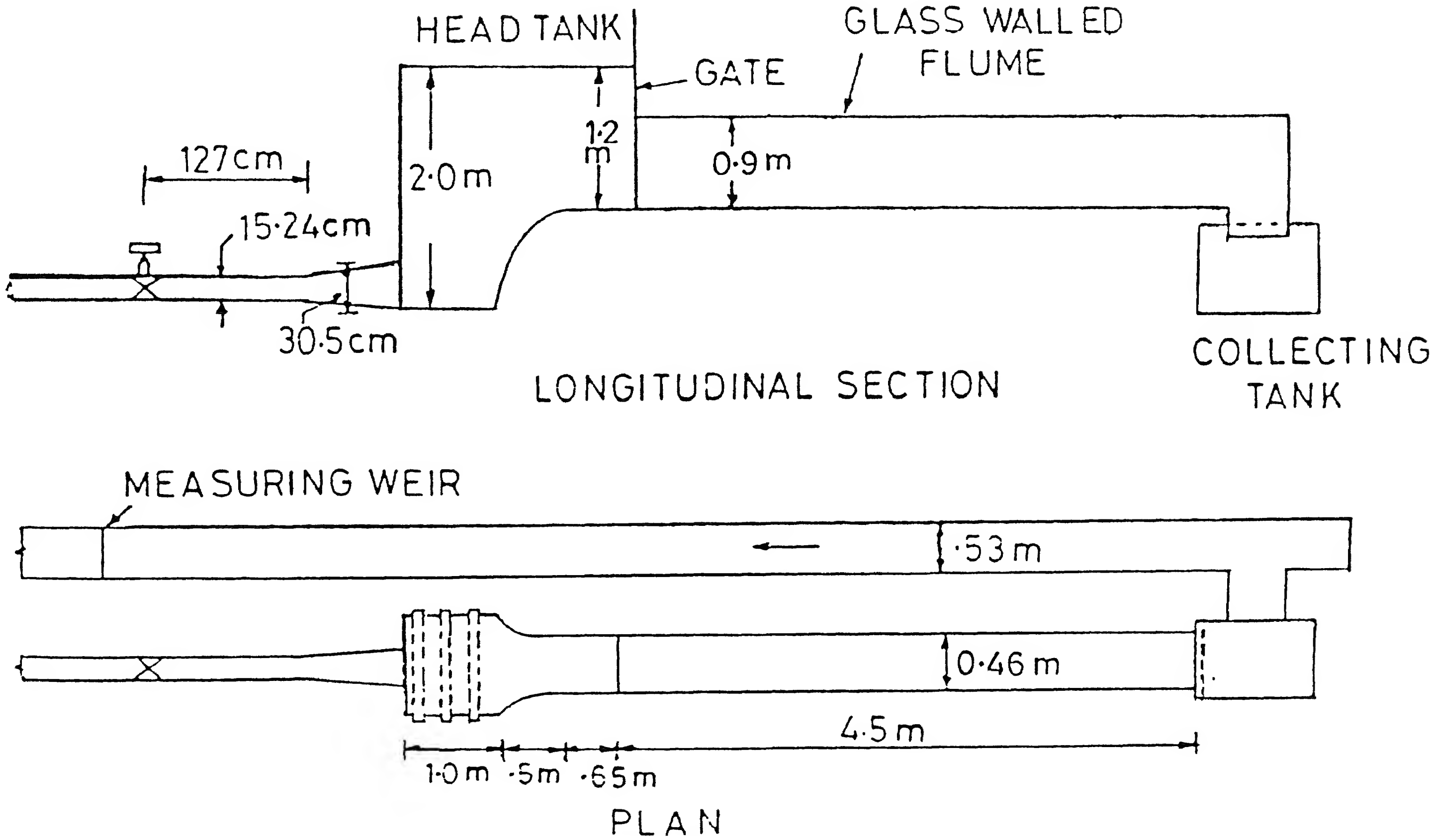


FIG. 4·2 SCHEMATIC VIEW OF THE EXPERIMENTAL EQUIPMENT

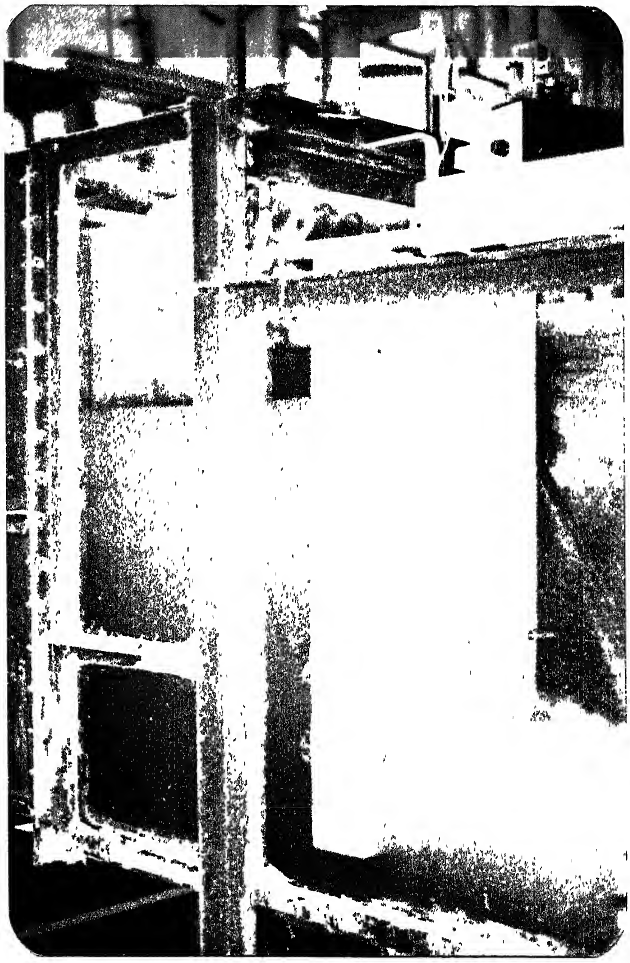


FIG. 4.3 PHOTOGRAPH SHOWING THE VERTICAL LIFT GATE

FIG. 4.4 PHOTOGRAPH SHOWING THE EXPERIMENTAL GLASS WALLED FLUME

CHAPTER - IV

EXPERIMENTAL DETAILS

4.1 EQUIPMENT

The experiments were conducted in a water flume with 5.0 m. long, 46.0 cm wide and 90.0 cm deep glass section. A vertical lift gate fabricated out of aluminium sheet 1/16" thick was supported vertically on an aluminium cantilever. This type of support simulates the elastic support of prototype of the gate. Clearance of 5 mm between the gate model and the side walls were found necessary to minimize corner eddy effects and to maintain a quasi two dimensional flow. A low damping guidance was provided for motion in the vertical direction by two roller bearings connected to gate model in a vertical plane so that the gate had a single vertical degree of freedom.

The downstream depth in the flume was varied by controlling the downstream gate fixed in the flume. Discharge was computed by measuring the head of the water over a rectangular sharp crested weir in the discharge channel.

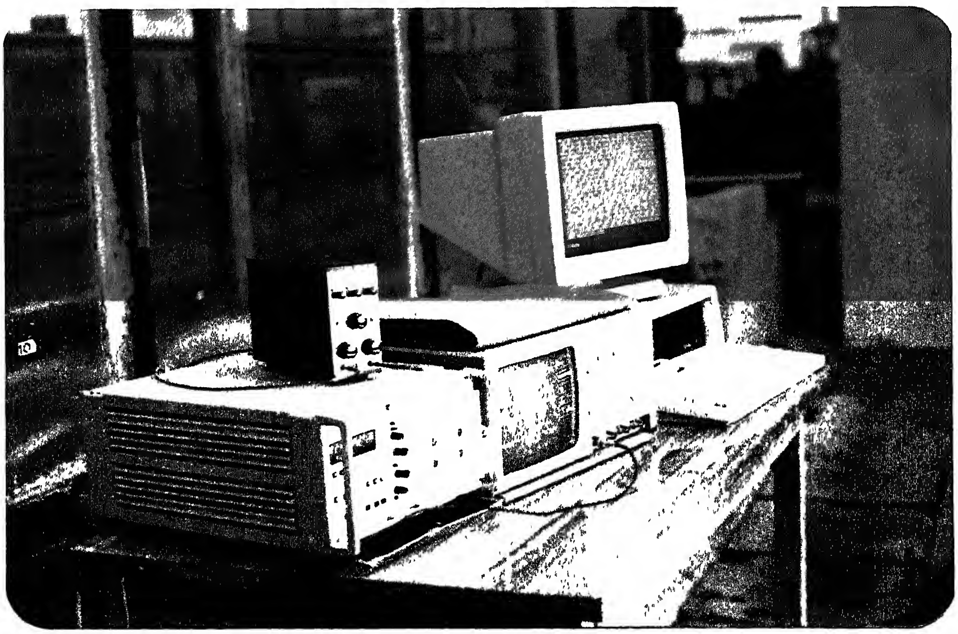


FIG. 4.5 PHOTOGRAPH SHOWING THE INSTRUMENTATION

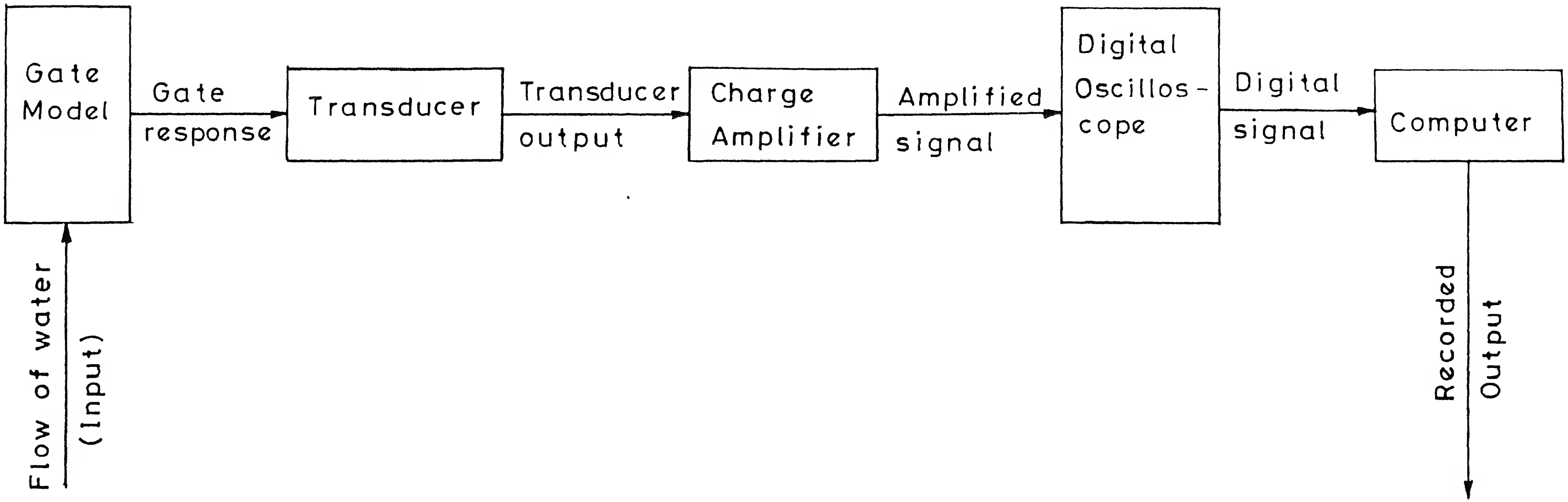


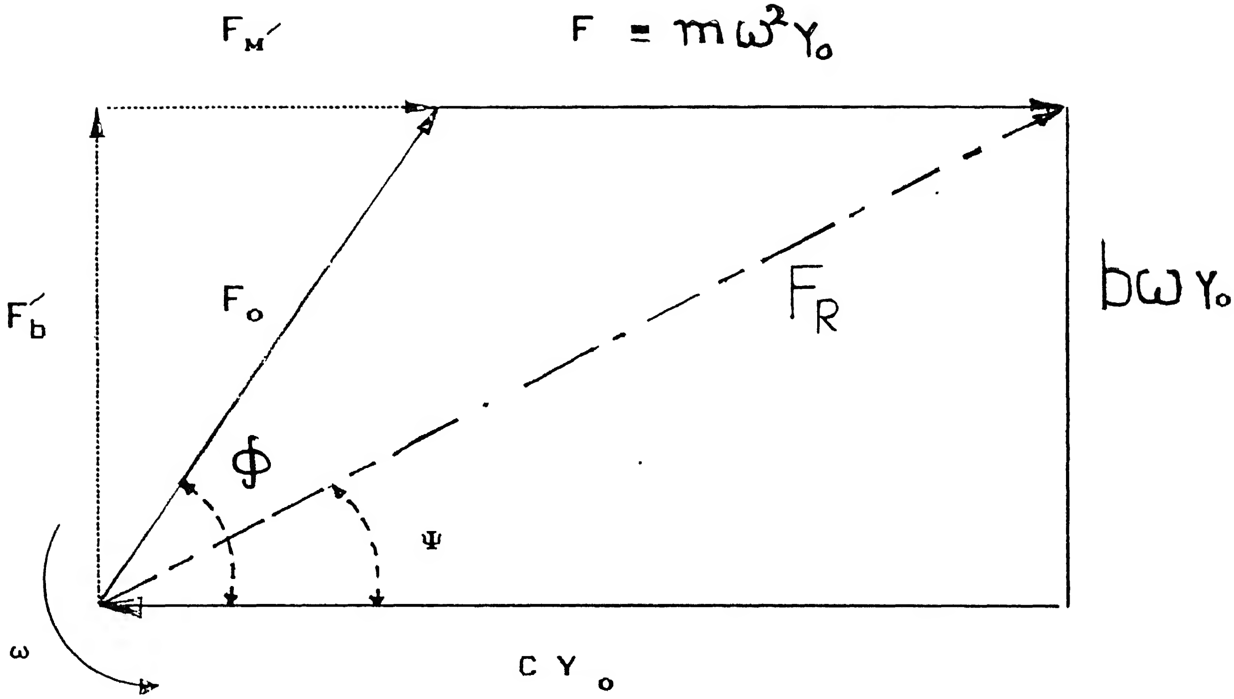
FIG. 4·6 BLOCK DIAGRAM OF EXPERIMENTAL PROCESS

4.2 INSTRUMENTATION

The experimental setup to determine the vibration characteristics of the model is shown in photographs 4.3 to 4.5 and figures 4.1 & 4.2.The block diagram of experimental setup is also presented in fig 4.6.

An aluminium cantilever beam of cross section 25 mm x 10 mm supported a hollow rectangular box type gate model of width 45.0 cm. across and 10.0 cm. along the water flow. An inductive displacementtransducer (W10 B&K type) was connected to the vertical arm of the cantilever. One accelerometer (B & K type 4381) was mounted with screw connection on the plate provided on the gate. A thin layer of grease was applied on the mounting surface before tightening down the accelerometer to improve mounting stiffness. The tapped hole in the machined part was such that the stud was not forced in to the base of the accelerometer. Two piezoelectric force transducers (B & K type 8200) were mounted sandwiched between two plates on the top of the gate model. The cable used with the accelerometer was shielded to prevent noise and clamped on the surface The signal from the transducers were amplified and stored in a storage oscilloscope (HP type 54501A) .

With this arrangement it was possible to measure the vertical gate displacement Y(t) and the dynamic component of resultant vertical force $F_R(t)$ acting at location of the



F_o = Fluid-force component

F_R = Resultant-force component measured at vibrating gate

FIG. 4.7 FORCE VECTOR DIAGRAM IN FREQUENCY DOMAIN

vibrating gate where the force transducers were mounted, When the gate was free to vibrate in the vertical direction. From the free body diagram of the gate from below the location of force transducers, it would be clear that vector sum of the net exciting fluid force F and the internal reaction force of vibrating gate mass ie ,

$$F_R = F_o + F_m \qquad \text{(with } F_m = m\ddot{y}\text{)}$$

From the knowledge of the Fourier transformed value of the amplitude (Y_o), the frequency (ω), and phase angle (ϕ) for the dominant vibration component, it was possible to determine the magnitude F_o and the phase angle ϕ of the net fluid force component of the same frequency ω by method of the force vector diagram (fig 4.7).

4.3 PROCEDURE

A gate model of d = 10.0 cm. and weight 8.23 Kg was used . The gate was connected to a support by means of an L - shaped cantilever. A number of holes were made on the vertical arm of the flat to enable setting of the desired gate opening. A cantilever span of 15 cm was used. For each gate opening, the downstream depth was varied with the help of a downstream control gate. The discharge was measured with the help of a sharp crested full width weir. The velocity of the jet V_j underneath the gate was calculated as follows :

$$Q = 0.837\ h^{1.45} \quad m^3 / sec$$

where h = head over the crest of the rectangular weir (m) and

V_j = Q / area of gate opening

Fig 4.2 shows the schematic view of the experimental equipment. Various photographs can also be seen to have a clear picture of the setup.

For signal analysis the transducers were connected to charge amplifiers for amplification of signals and the amplifiers were connected to a storage oscilloscope. This in turn was connected to a PC in which a GPIB interface card was installed. The signal was first stored in the storage oscilloscope and then transferred to the PC.

For determination of damping characteristics the displacement signal was stored for various depths of still water in the flume. The deflection of the model gate under various loads was found out with the help of the displacement transducer.

Spectral analysis of the resultant force and gate displacement signal was performed with FFT software on the HP main frame computer. The results were plotted in the form of normalized force and displacement auto-power spectra. The phase angle ϕ between the resultant force and the gate

displacement was obtained from cross-spectral analysis software.

4.4 SPECIFICATIONS

4.41 OSCILLOSCOPE

Model number	:	HP 54501 A Digitizing oscilloscope
Manufacture	:	Hewlwett Packard
No. of input channels	:	4
Input coupling	:	AC , DC
Storage mode	:	Oscilloscope digitizes the input signal before displaying the trace
Normal mode	:	Behaves like a conventional analog instrument
Vertical sensitivity	:	Maximum 5 mv/div
	:	Minimum 5 v/div
Vertical gain accuracy (dc)	:	+ 1.5 %
Time base accuracy	:	0.005 %
Time base range	:	2 ns/div to 5 s/div
Maximum sample rate	:	10 Msa/s
Memory depth	:	501 Points (display)
	:	1024 Points (via HP-IB)
Signal averaging	:	1 to 1024

4.42 AMPLIFIER FOR DISPLACEMENT TRANSDUCER

Type	:	ALPHA 3000
Manufacturer	:	Hottinger Baldwin Messtechnic GMBH
Measuring range	:	± 10 V
Measuring rate	:	25 Hz
Input & Output control signals	:	T T L level
Linearity division	:	< 0.01 %
Interfaces	:	IEEE 488-78 RS 232-C

4.43 CONDITIONING AMPLIFIER

Type	:	Charge Amplifier Type 2635
Manufacturer	:	Bruel & Kjaer ; Denmark
Charge input	:	Via 10 - 32 NF and BNC coaxial socket
Maximum input	:	$\simeq 10^5$. pC
Sensitivity conditioning	:	0.1 to 10.99 pC / ms^{-2}
Amplifier sensitivity	:	0.01 mv to 10 v / pC
Signal Output	:	Via 10 - 32 NF and BNC coaxial socket
Maximum Output	:	8 v (8 mA)
Frequency range	:	2 Hz to 100 KHz (Acceleration) 10 Hz to 10 KHz (velocity) 10 Hz to 1 KHz (Displacement)

Power requirement	:	Three 1.5 Alkaline cells or +6 to +28 V single or ± 14 dual polarity DC

4.34 ACCELEROMETER

Type	:	B & K type 4381
Manufacturer	:	Bruel & Kjaer ; Denmark
Charge sensitivity	:	10.0 ± 2.0 % pC / ms^{-2}
Voltage sensitivity	:	≃ 8.0 mV / ms^{-2}
Frequency range	:	4.8 KHz
Weight	:	43.0 grams

4.35 FORCE TRANSDUCER

Type	:	B & K Type 8200
Manufacture	:	Bruel & Kjaer ; Denmark
Force range	:	1 KN tensile to 5 KN compressive
Linearity	:	< ± 1.0 % of maximum force
Charge sensitivity	:	4.0 pC / N
Stiffness	:	5.0×10^{8} N / m
Weight	:	21 gram

4.36 INDUCTIVE DISPLACEMENT TRANSDUCER

Type	:	W 10 K
Manufacturer	:	Hottinger Baldwin Messtechnic GMBH
Nominal displacement	:	± 10 mm

Nominal sensitivity	:	± 80 mv / v
Nominal Output signal span	:	160 mv / v
Linearity Deviation	:	< ± 0.4 %
Carrier frequency	:	5 KHz
Maximum cable length	:	500 m
Weight (with plunger)	:	40.0 gms.

CHAPTER - V

RESULTS AND DISCUSSION

The results are tabulated in Table # 1 to 3. The recorded measured signals are shown in Appendix - A . The spring constant of elastic support is calculated both, by equation given in the chapter III and by load deflection curve. It has come out as 117.64×10^3 N/m. The coefficient of critical damping and coefficient of damping for various depths of still water from bottom of the channel is given in Table # 1. It is observed from Table # 1 that the coefficient of damping decreases with increase in depth of still water in the flume.

The influence of various parameters on vibration is shown in Table # 2. The Reynolds number $V_j\ s / \nu$ lies between 145000 to 180000 and one interesting thing observed here is that this Reynolds number increases with increasing gap ratio (s/d) but decreases with increasing downstream water depth for the same gap ratio.

Table # 3 throws some light on the relationship between the gap ratio and the mean amplitude of the measured signals of displacement and force. This mean value of gate

displacement and excited force is averaged over a sufficient time interval. The influence of gate opening on force and displacement magnitude can be seen in Table # 3.

Results for the phase angle between fluid force and gate displacement are presented in fig. 5.5. As the gap ratio increases the phase angle ϕ is observed to decrease starting from 90 degree. In order to find the most critical flow situation with respect to vertical gate vibrations the normalized power density function of displacement vs frequency is plotted in fig. 5.6. It is observed with the help of fig. 5.6 that the peak of the spectra for the free vibrations match with the peak of spectra for gate vibration with gap ratio 0.65 . Also from Table # 3 we see that the maximum mean displacement occurs for the case of gap ratio 0.65 Hence we can say that the most dangerous vibrations were found at the gap ratio 0.65 .

For understanding the nature of vibrations, the power spectra of the force on a elastic gate (S_{FF}) and the response of an elastic gate (S_{YY})are plotted in fig.5.7 to fig5.12. These spectra are plotted in a normalized form using normal scales for various gap ratios and downstream water depth. The linear dependence of dominant excitation frequency on flow velocity and gap ratio for the rigid gate and the resonance character of the response for the elastic gate are clear indication of vortex excitation .

For the clear visualization of the vortex pattern underneath the gate for various gap ratios and downstream water depths photographs have been taken and shown in fig. 5.13. Visualization of the shear flow zone underneath the gate reveals that the broad-banded peaks in these force (elastic gate) spectra are associated with large scale vortices.

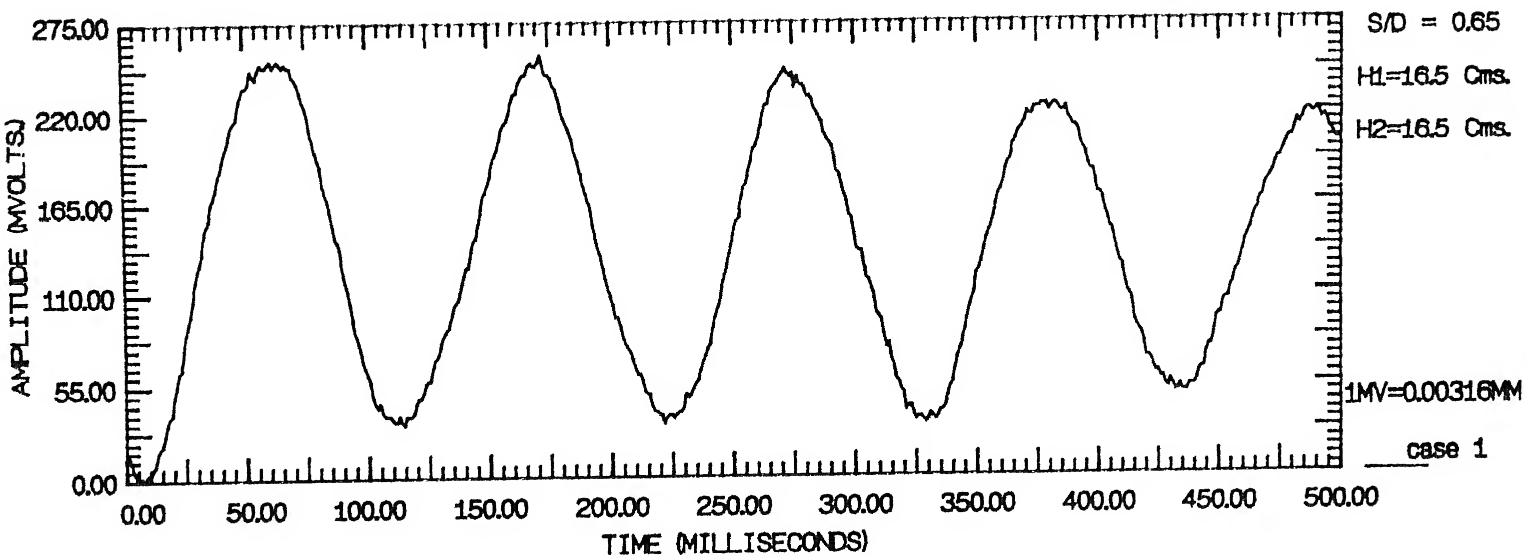


FIG. 5.1 DAMPING AND STIFFNESS CHARACTERISTICS FOR 16.5 CM.

WATER DEPTH WITH GAP RATIO 0.65

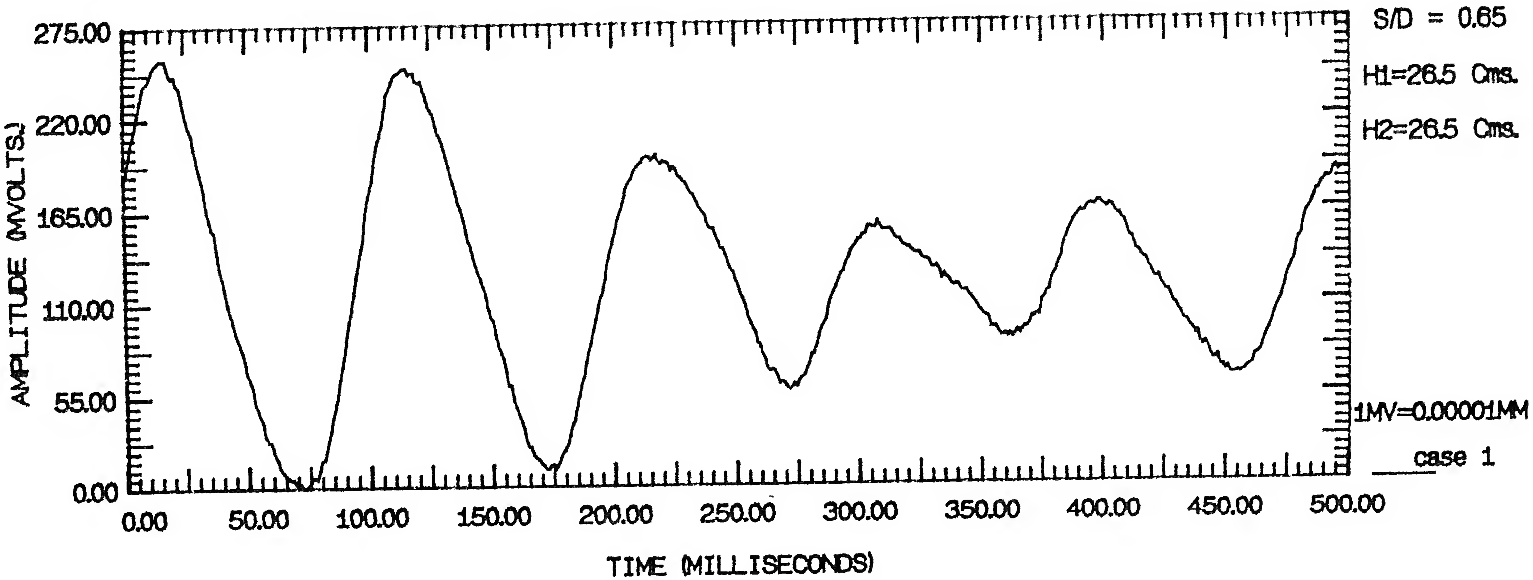


FIG. 5.2 DAMPING AND STIFFNESS CHARACTERISTICS FOR 26.5 CM.

WATER DEPTH WITH GAP RATIO 0.65

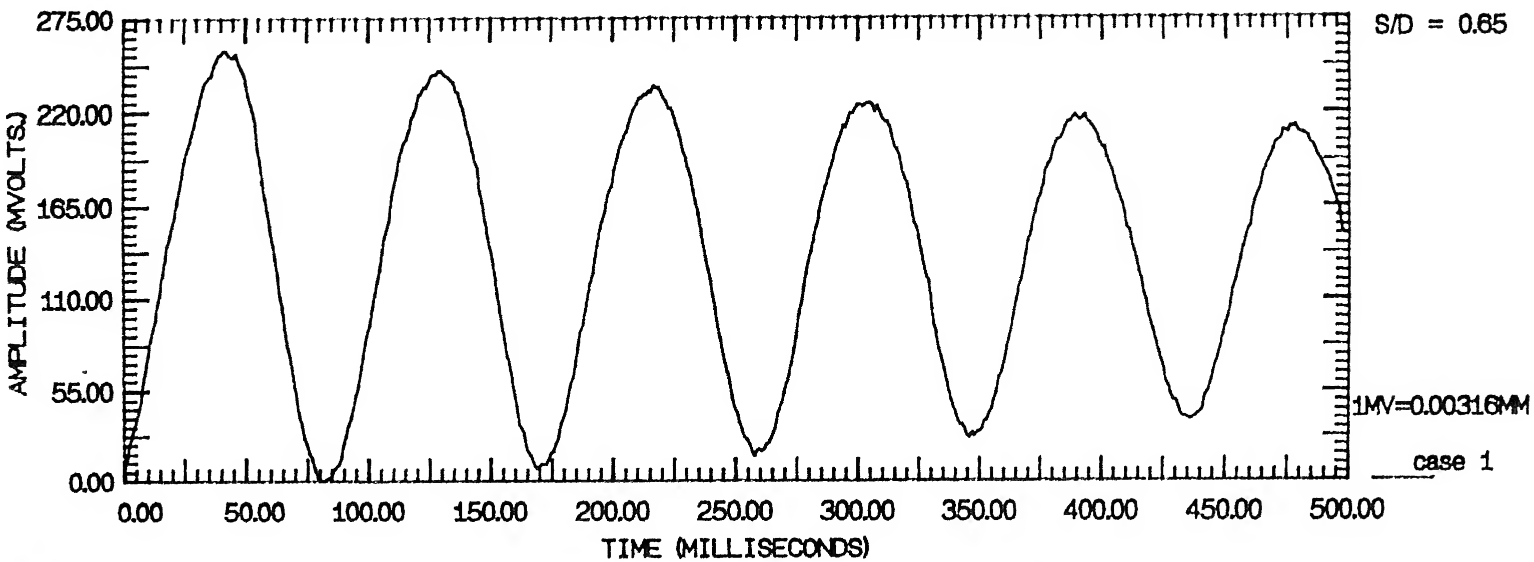


FIG . 5 . 3 DAMPING SIGNAL OF GATE WITHOUT WATER

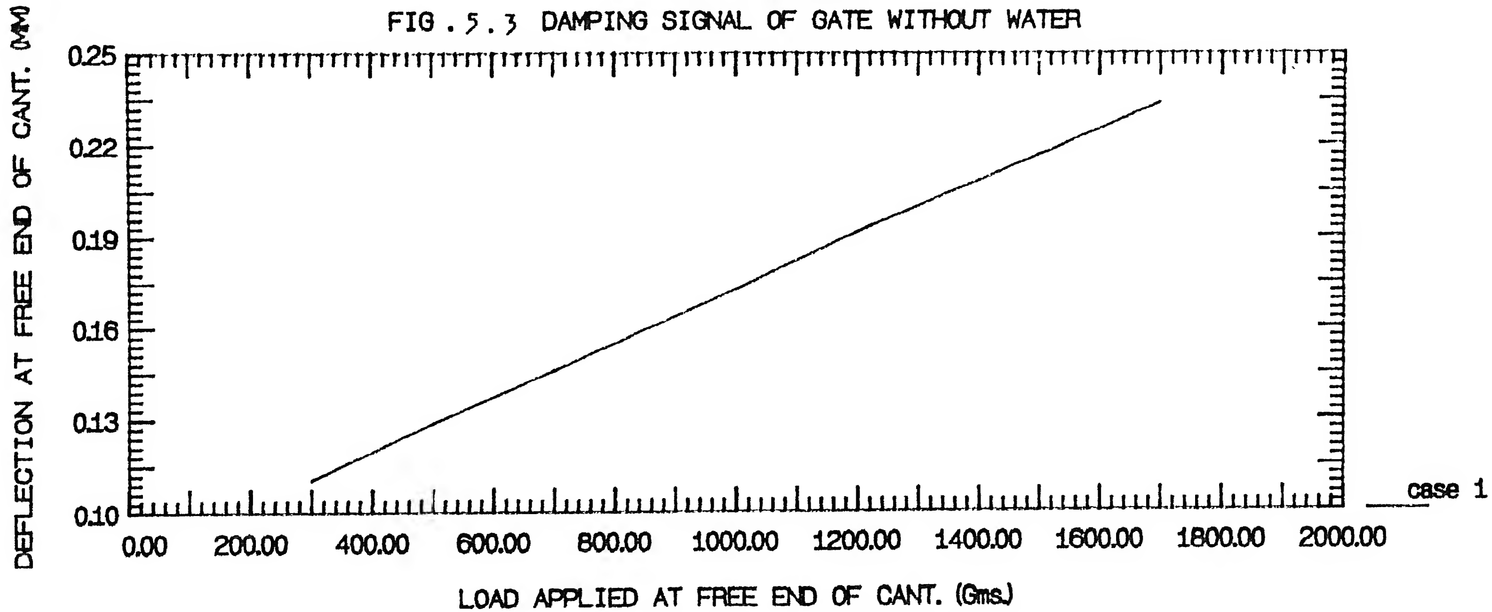


FIG. 5 . 4 LOAD VS DEFLECTION CURVE

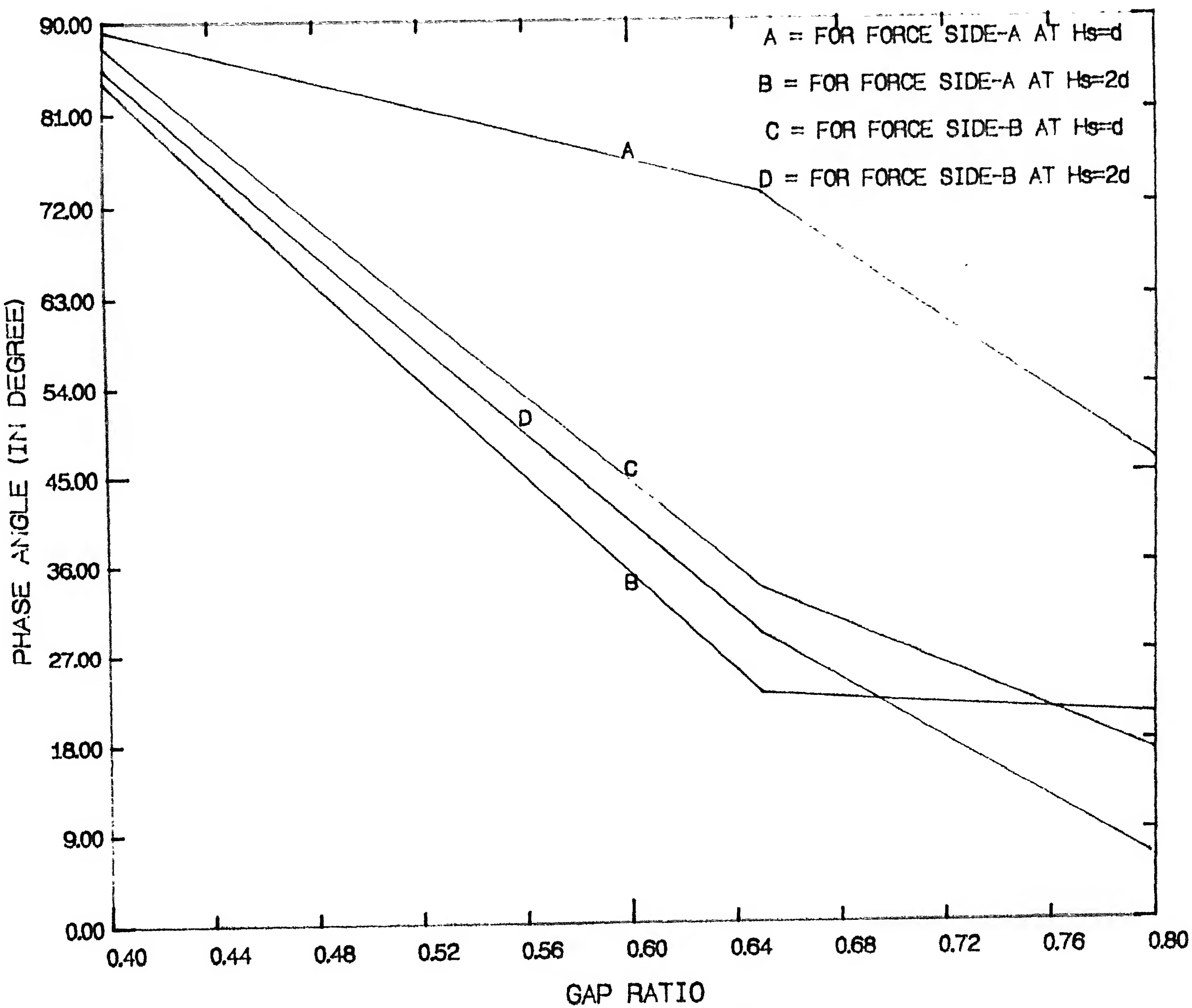


FIG. 5.5 GAP RATIO VS PHASE ANGLE CURVE

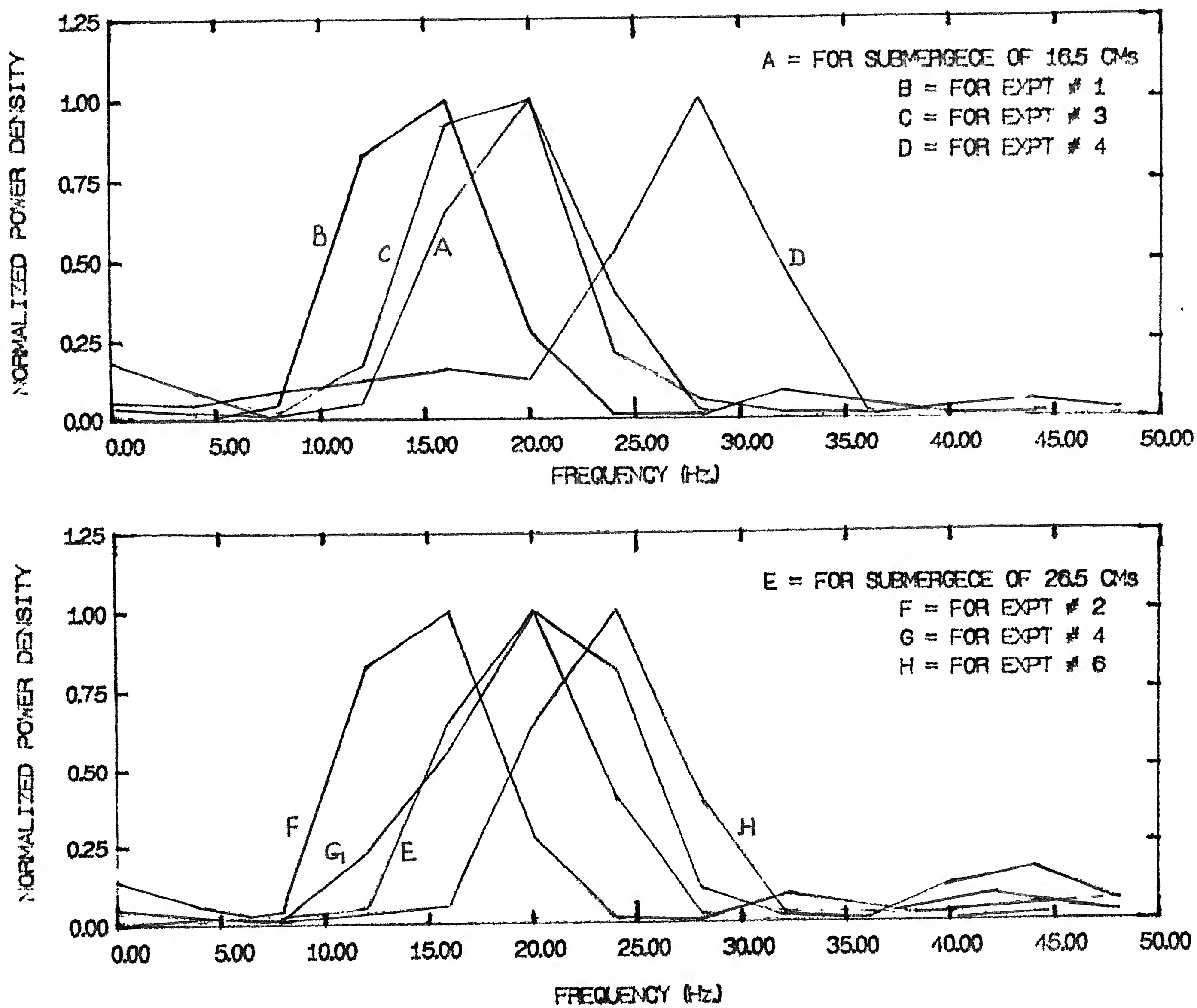


FIG. 5.6 POWER SPECTRA OF DISPLACEMENT

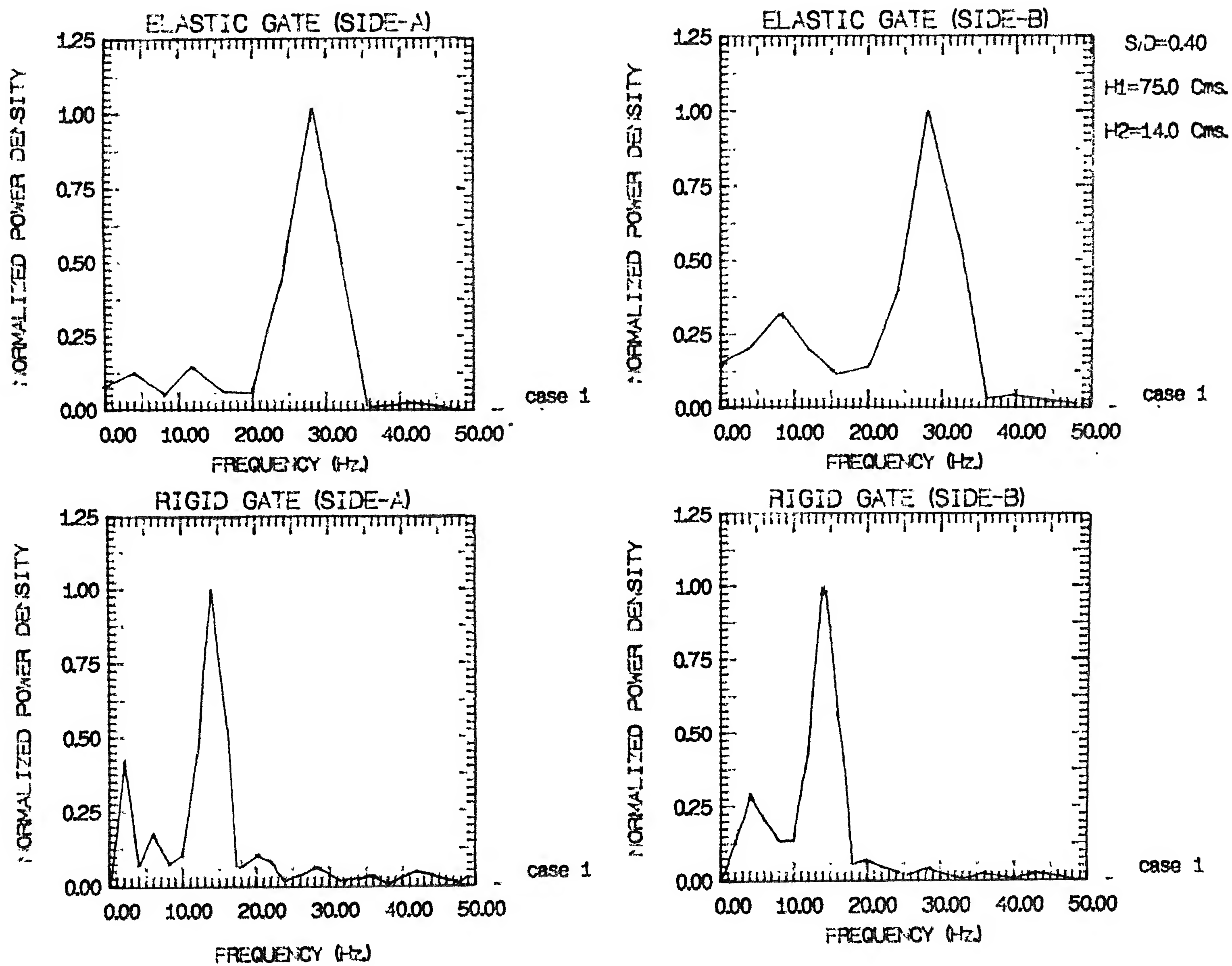


FIG.5.7 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 1

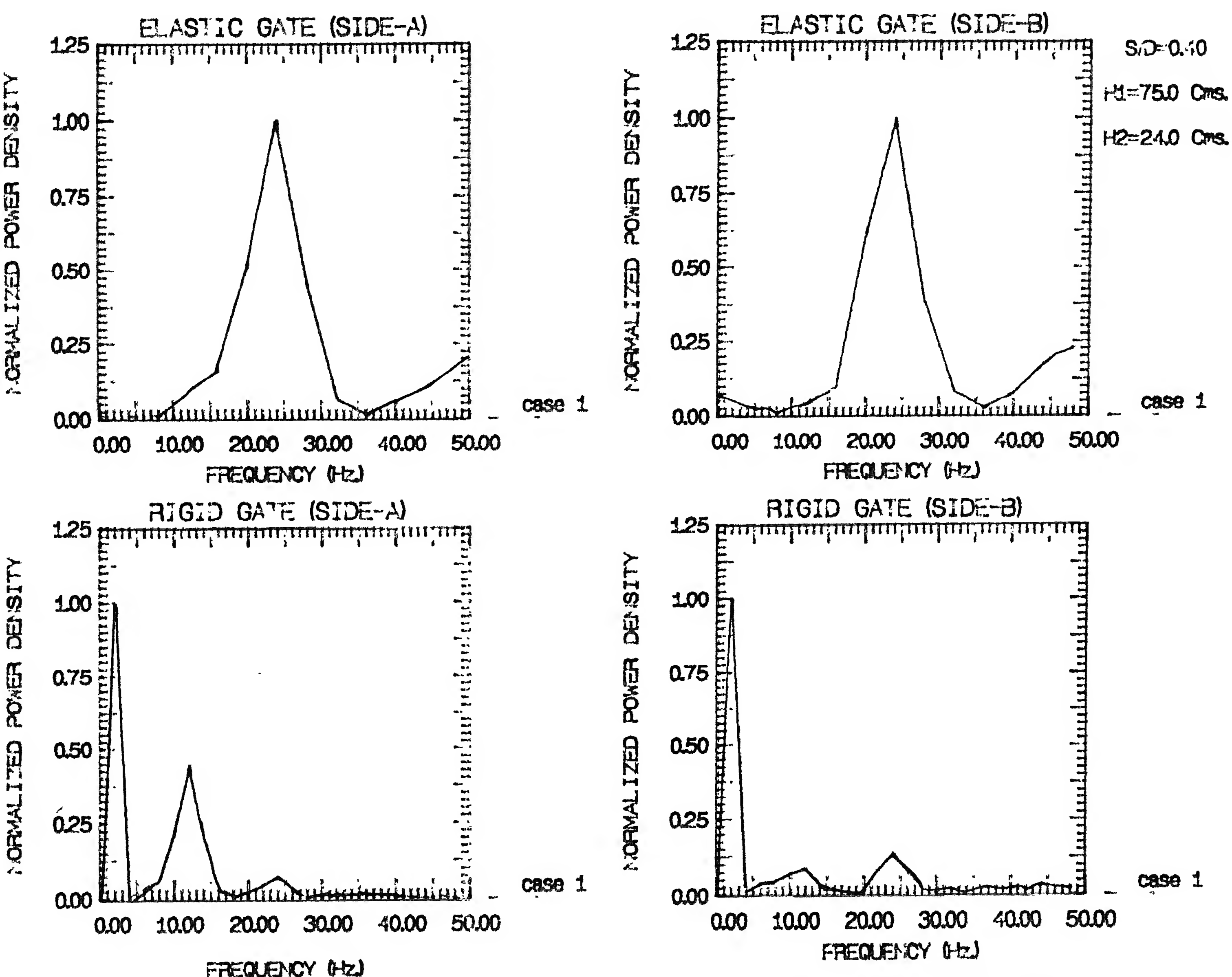


FIG.5.8 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 2

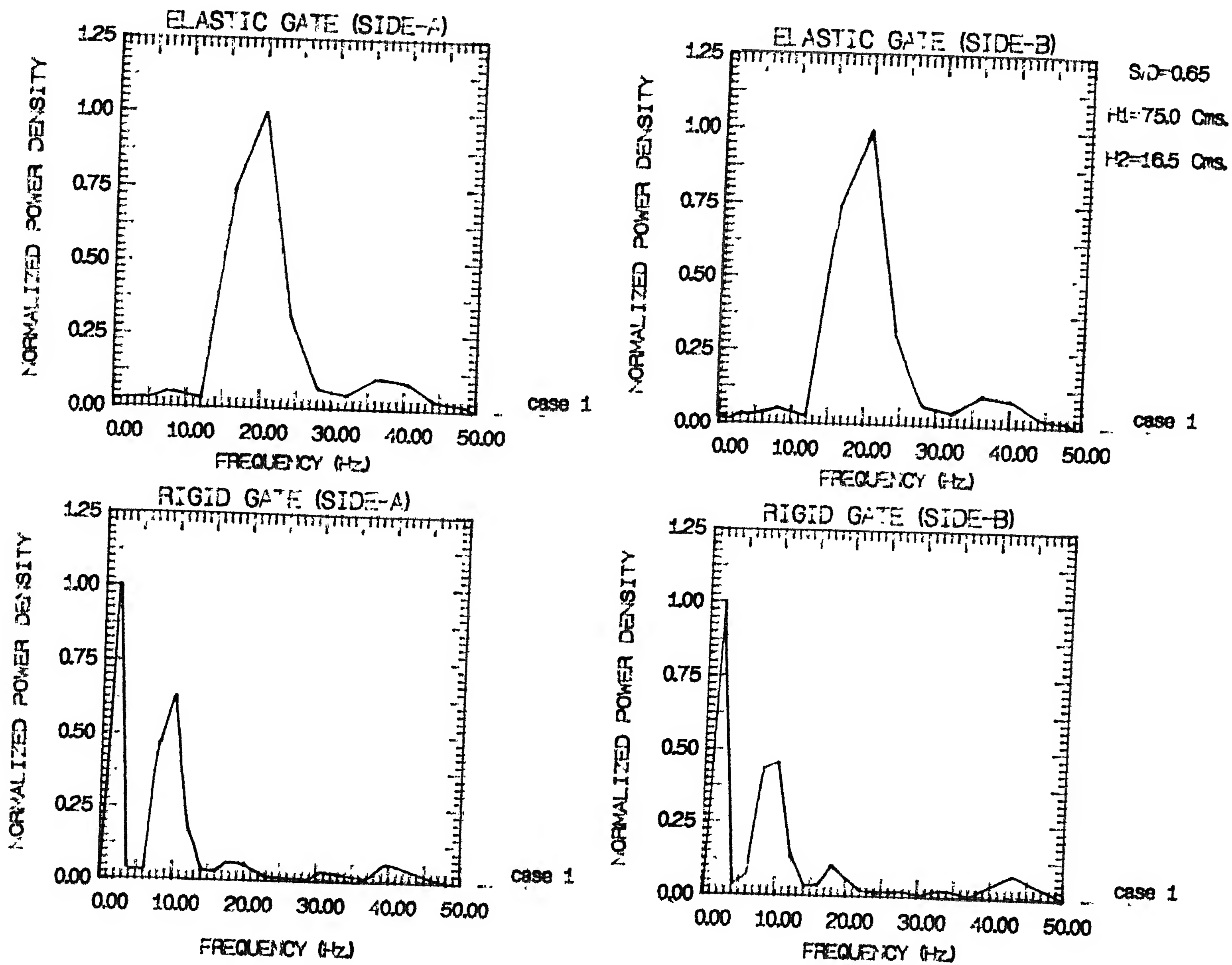


FIG.5.9 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 3

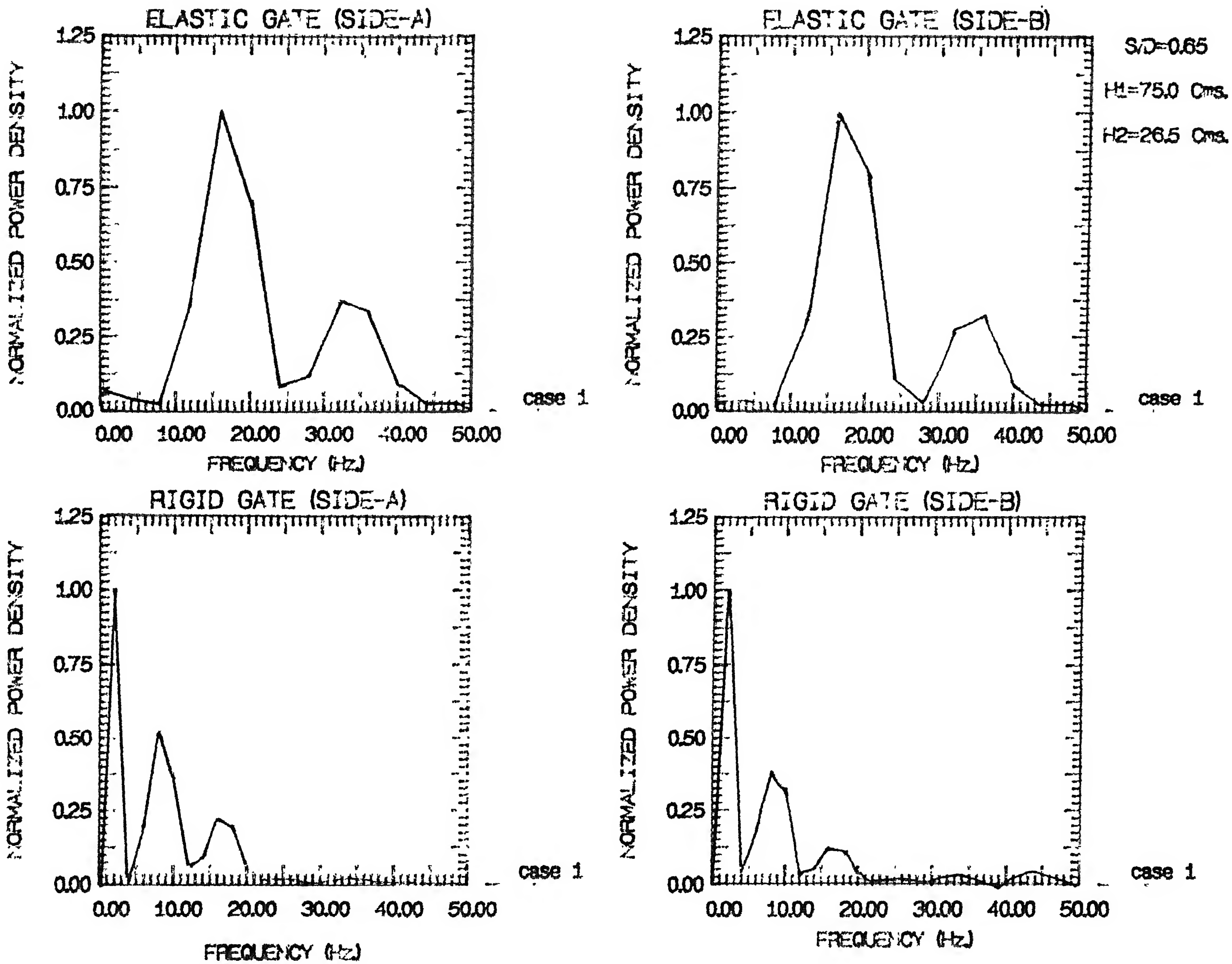


FIG.5.10 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 4

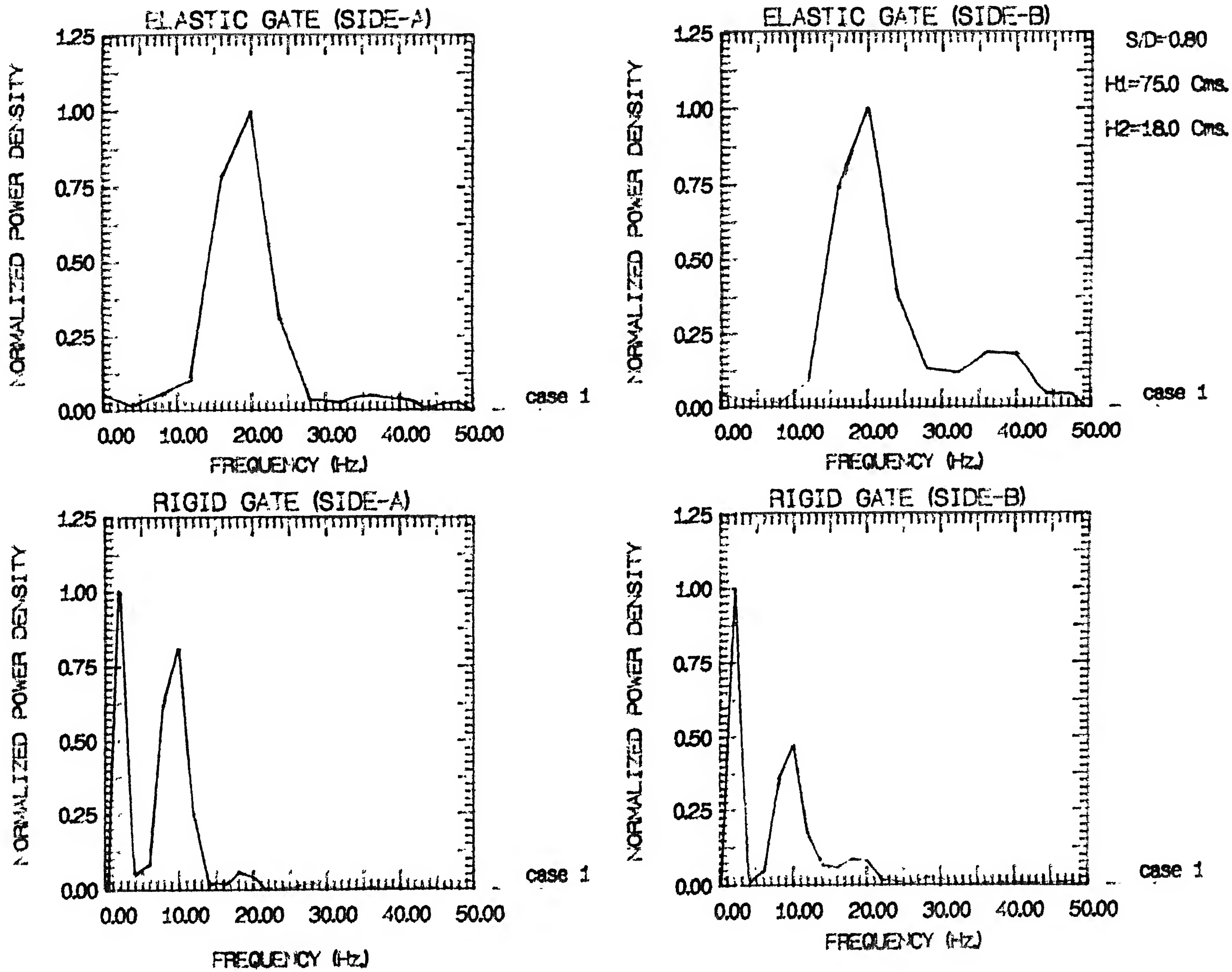


FIG.5.11 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 5

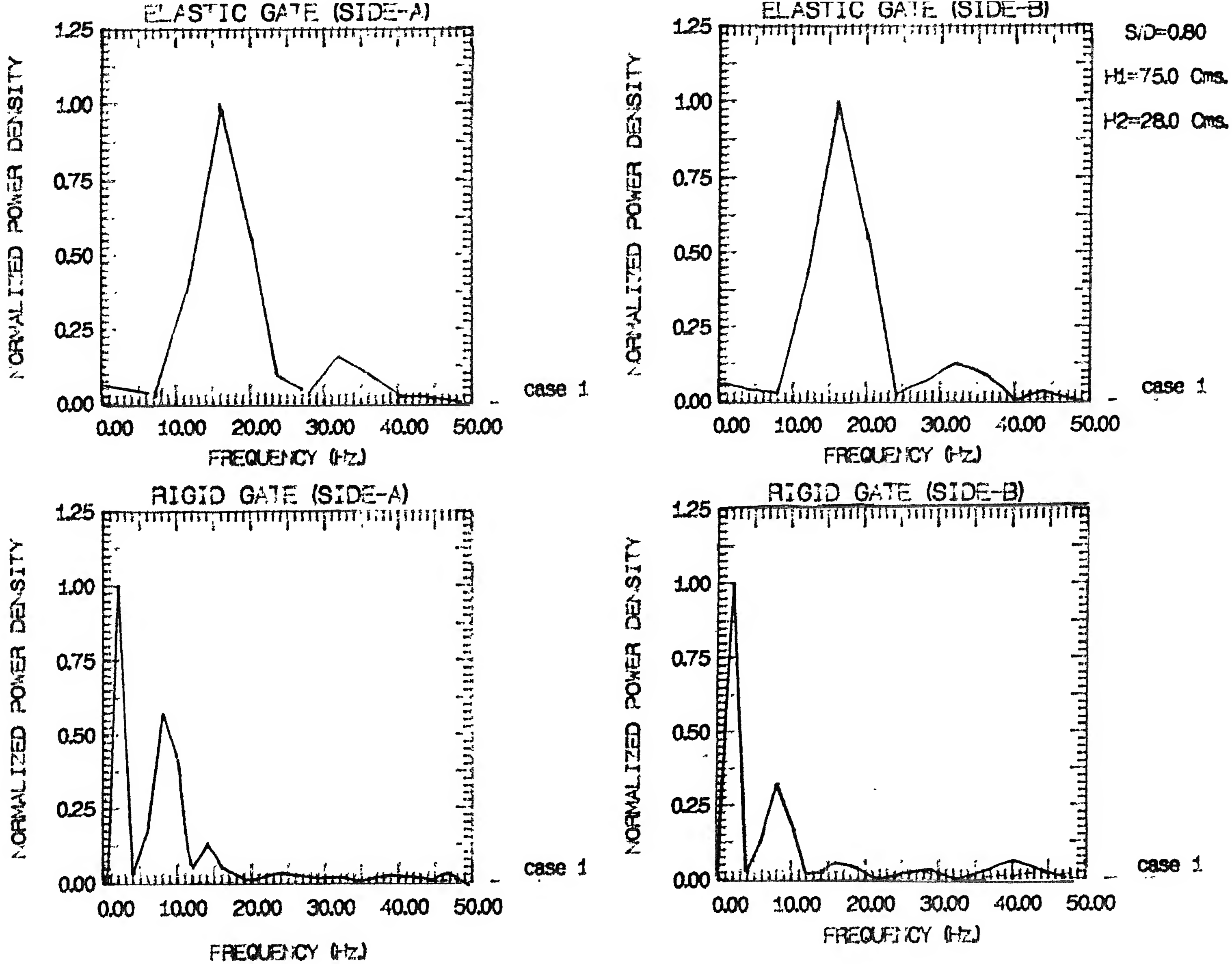


FIG.5.12 NORMALIZED POWER SPECTRA OF FORCE FOR EXPERIMENT # 6

FIG. 5.13 PHOTOGRAPH SHOWING THE SHEAR FLOW ZONE UNDERNEATH THE GATE

TABLE # 1

DANMPING CALCULATION FOR GATE MODEL

Gap ratio = 0.65

Spring constant of elastic support = 11.764 Kg/mm

Natural frequency in air = 19.0168 Hz

coefficient of critical damping C_c = 200.485 Kg-sec/m

Depth of still water from bottom of channel (Cm)	Cofficient of damping C (Kg-sec/m)
0.00	1.3343
16.5	2.7240
26.5	6.4461

TABLE # 2

Kinematic viscosity of water at 20^{o} C = 10^{-6} m^2/sec

weight of gate = 8.23 Kg f_n=19.0168 Hz

Acceleration due to gravity = 9.81 m/sec^2

Expt No.	Gate opening s cm	Gap ratio s/d	U/S water depth h_1 cm	$\frac{h_1}{d}$	D/s water depth h_2 cm	$\frac{h_2}{d}$	$V_j = \frac{Q}{s\ b}$ m/s	Reduced velocity $V_r = \frac{V_j}{f_n\ d}$	Reynolds number $Re = \frac{V_j\ s}{\nu} \times 1000$	Reynolds number $Re = \frac{V_j\ d}{\nu} \times 1000$
1	4.0	0.40	75.0	7.50	14.0	1.40	3.647	1.918	145.88	364.72
2	4.0	0.40	75.0	7.50	24.0	2.40	3.595	1.890	143.80	359.56
3	6.5	0.65	75.0	7.50	16.5	1.65	2.689	1.414	174.79	268.95
4	6.5	0.65	75.0	7.50	26.5	2 65	2.575	1.355	167.38	257.53
5	8.0	0.80	75.0	7.50	18.0	1.80	2.254	1.186	180.32	225.40
6	8.0	0.80	75.0	7.50	28.0	2.80	2.237	1.177	178.96	223.74

TABLE # 3

MEAN AMPLITUDE OF DISPLACEAND AND FORCE

AND PHASE ANGEL BETWEEN FLUID FORCE AND GATE DISPLACEMENT

Expt No.	Gap ratio	Mean amplitude of displacement (mm)	Mean amplitude of force (elastic gate) (newton)		Phase angle between fluid force and gate displacement (in degree)	
			Side-A	Side-B	Side-A	Side-B
1.	0.40	5.416	193.22	192.96	89.117	84.156
2.	0.40	6.186	194.68	194.15	87.565	85.353
3.	0.65	6.455	195.70	195.46	73.127	22.820
4.	0.65	6.196	200.31	199.24	33.535	28.894
5.	0.80	6.157	195.43	194.75	46.346	20.540
6.	0.80	6.151	194.12	194.06	17.039	6.113

CHAPTER - VI

CONCLUSIONS

The vibration characteristics of a vertical lift gate used to control flow depend on the geometry of the gate, upstream and downstream water depths, gap ratio, mass of the gate and damping characteristics of the gate. Using dimensional analysis, a functional relationship between the dominant amplitude of vibration and the above listed variables has been obtained. The new methodology for separate measurement of force, acceleration and displacement with help of transducers, amplifier and oscilloscope is used successfully. Spectral analysis of measured signals with the help of FFT software provides good knowledge about the nature of vibrations of vertical lift gate. The following conclusions can be drawn from the experimental study :

(i) Maximum vibration of the vertical lift gate occurs at a gap ratio of 0.65.

(ii) Vibration amplitude reaches a maximum at a submergence over the gate bottom ratio of about h_s /d = 1.0 and decreases continuously with increase in the h_s /d ratio.

(iii) The nature of the vibration can be explained with help of the power spectra of force on a rigid gate (S_{FF}) and of the response of an elastic gate (S_{YY}).

(iv) As the velocity increases beyond the vortex resonance range more and more energy is transferred from the fluid to the body.

The above conclusions are similar to those of Naudascher,E.,et.al., [11] .

6.1 DESIGN CRITERIA DERIVED FROM THE EXPERIMENT

Based on the conclusions the following design criteria can be formulated :

(i) Resonance frequencies of gate hoist systems and gate members should be well above the dominant frequencies.

(ii) Unstable flow separation and / or reattachment zone should be prevented.

(iii) Water surfaces unstable because of turbulence, waves, hydraulic jumps, water column separation, should have no opportunity to hit the structural surface.

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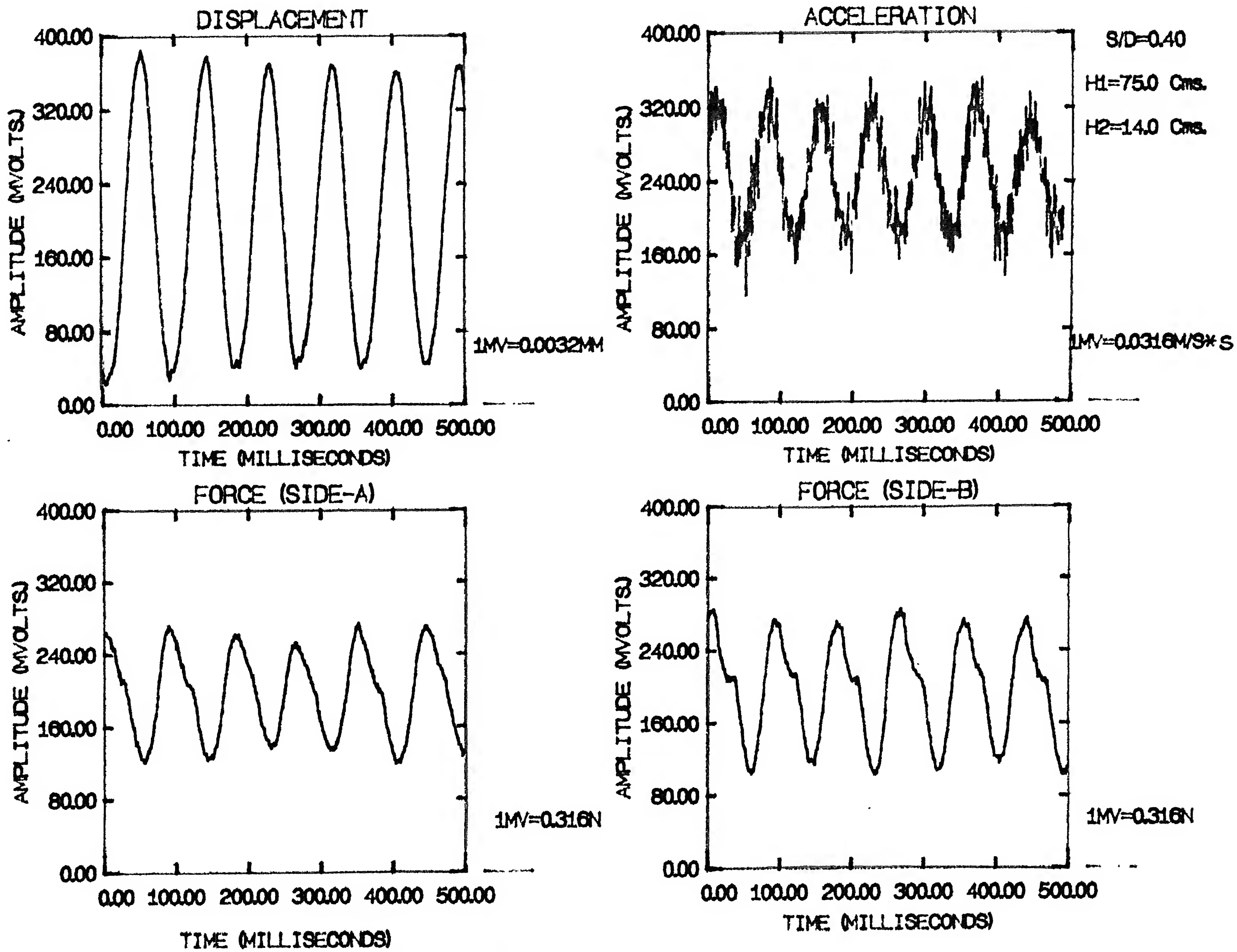

FIG. A.1 MEASURED SIGNAL FOR EXPERIMENT # 1

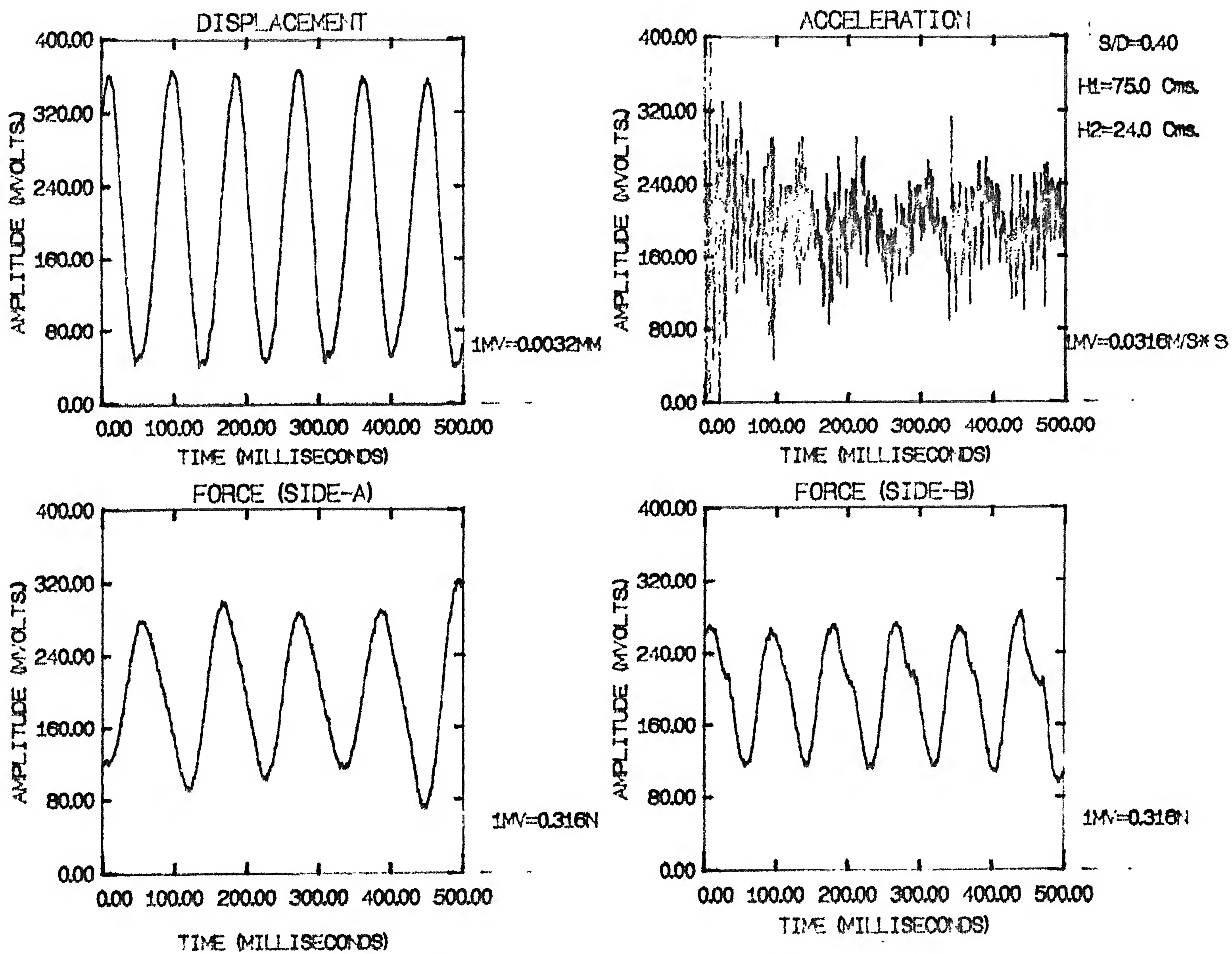

FIG. A.2 MEASURED SIGNAL FOR EXPERIMENT # 2

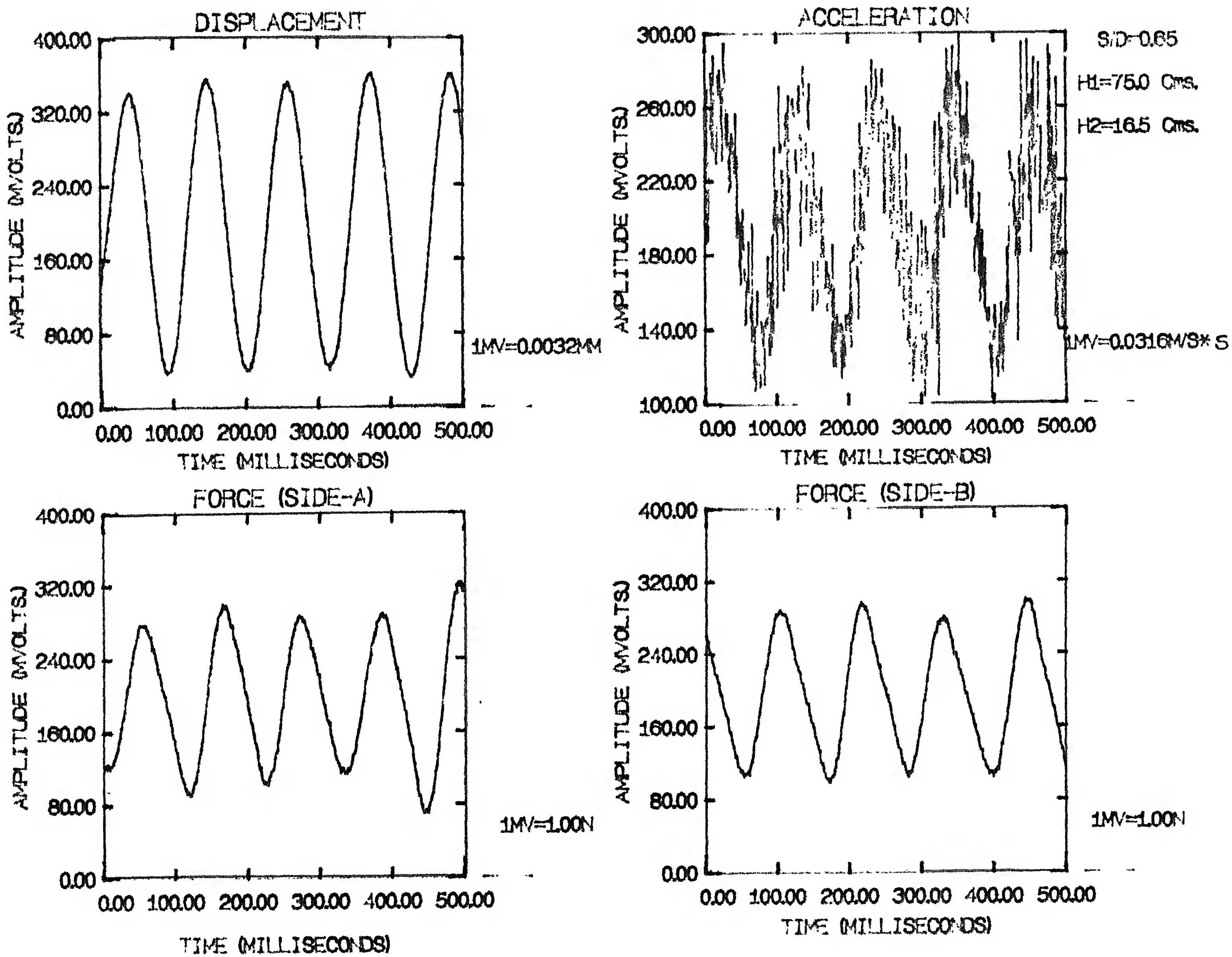

FIG. A.3 MEASURED SIGNAL FOR EXPERIMENT # 3

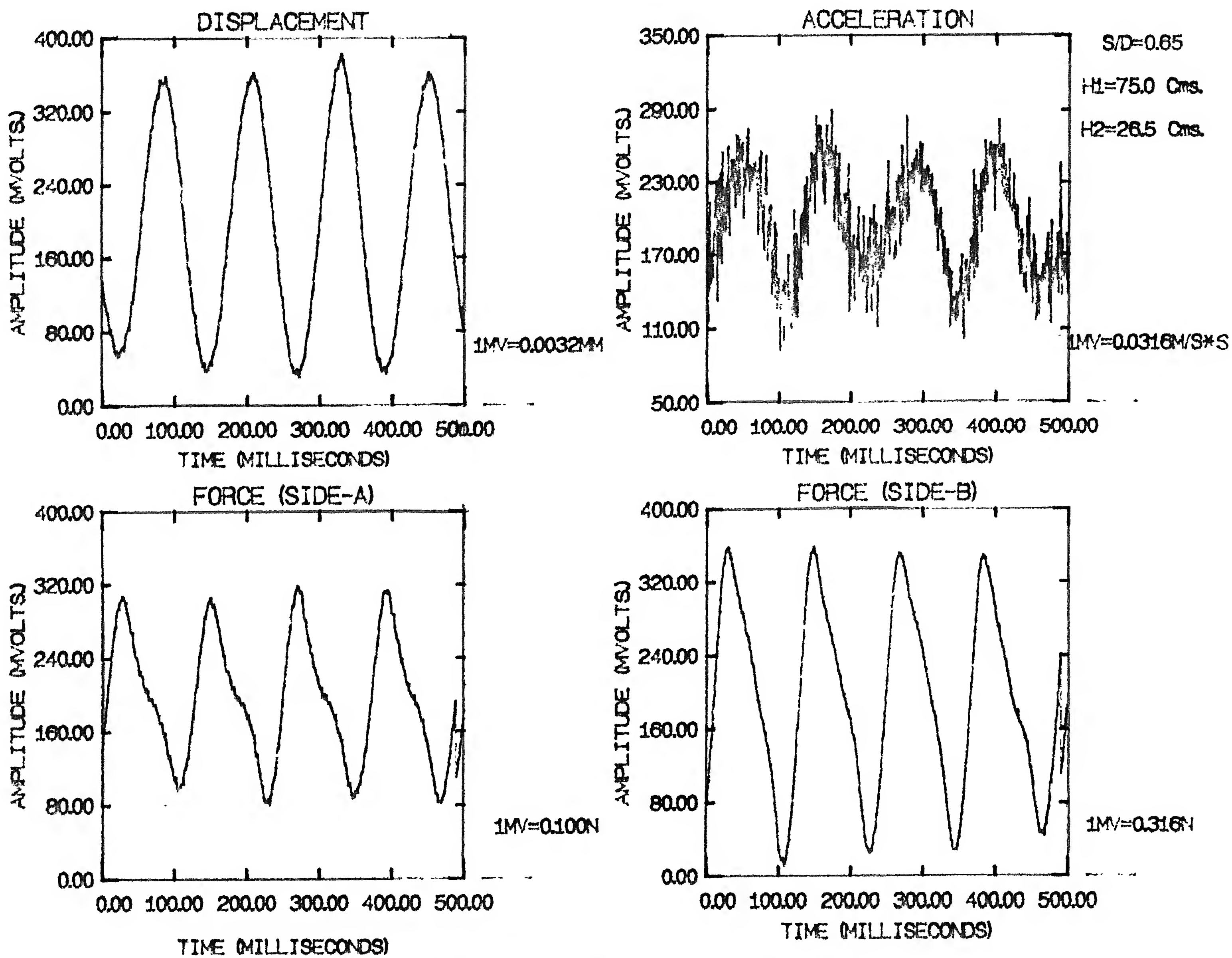

FIG. A.4 MEASURED SIGNAL FOR EXPERIMENT # 4

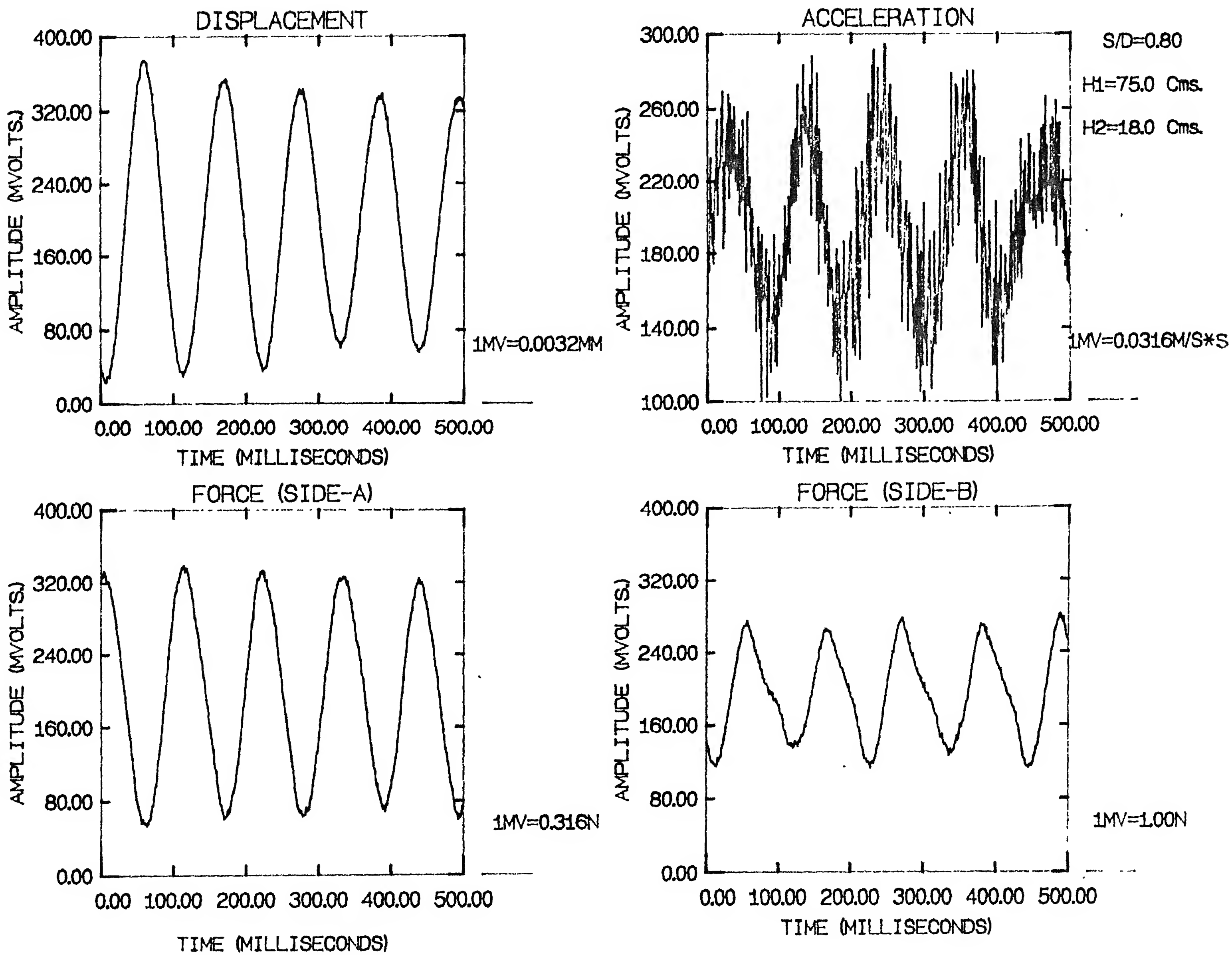

FIG. A.5 MEASURED SIGNAL FOR EXPERIMENT # 5

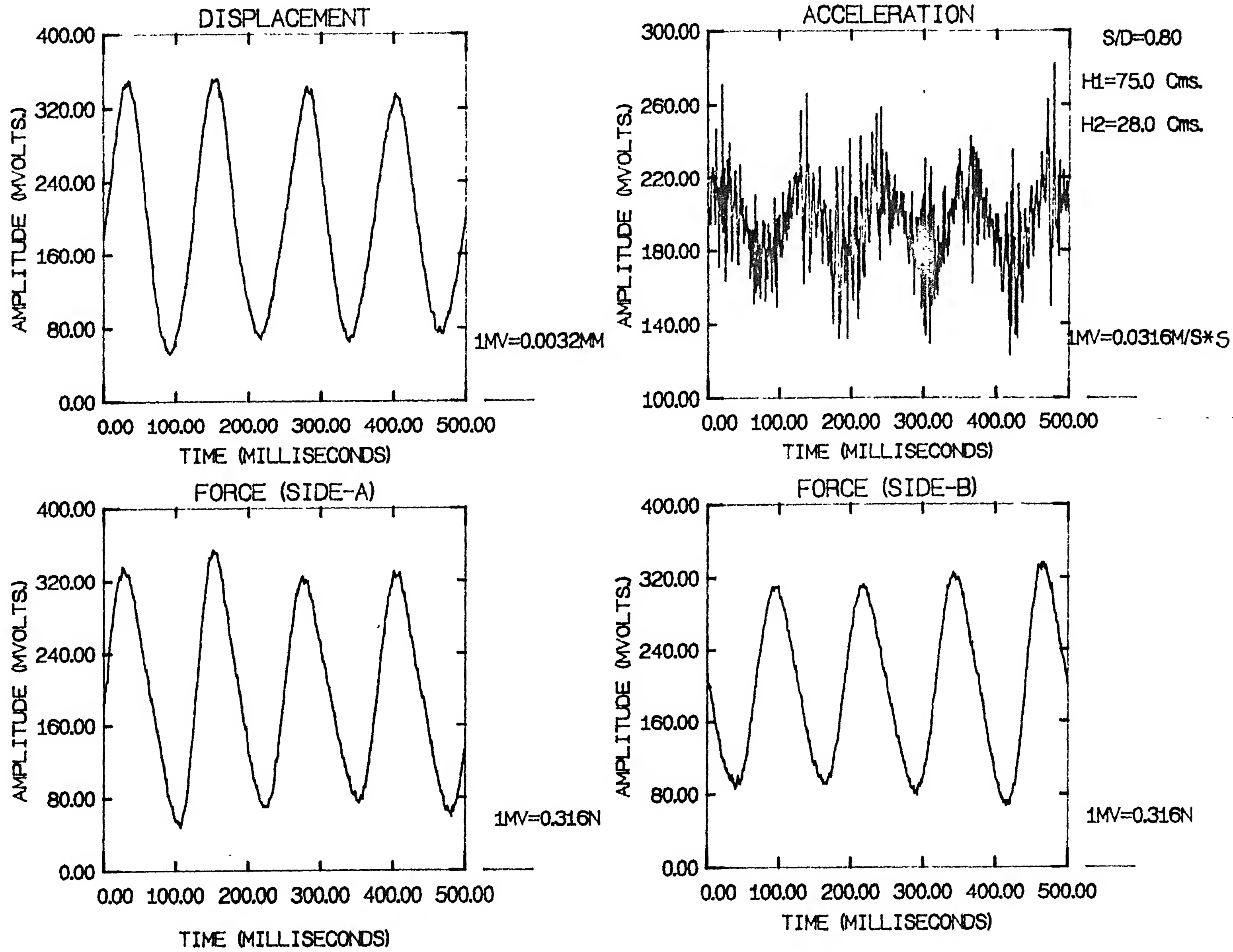

FIG. A.6 MEASURED SIGNAL FOR EXPERIMENT # 6

A P P E N D I X - B

DATA - ACQUISITION

Data Acquisition generally relates to the process of collecting the desired process in digital form, as rapidly, accurately, completely and economically as possible. Some form of storage is generally required to permit subsequent processing and, indeed, to carry out reprocessing at later time when different analysis procedures are seen to be required. For this purpose a data acquisition system which acts both as a buffer and a converter between the data source and analysis operation is required.

The real world events are continuous (or analog) in nature but computer is a digital device. Hence it requires a conversion of analog signal to digital form samples are quantified for digital processing by converting the sampled value into a equivalent numerical value by an analog to digital converter, each value is represented by a finite number of ON / OFF states of the solid state circuit.

In a data acquisition system the following operations are involved - generation of input signals by transducer, signal conditioning, data conversion (from

analog to digital and vice versa) data storage and display and finally, data processing. In the signal conditioner operation we have to amplify the weak input signal from transducer with the help of a charge amplifier.In this process we also filter out the unwanted frequencies originated from the transducer .The analog transducer output is converted into digital form using a analog to digital converter (A/D) built into the measurement system before data transmission to a personal computer.

After A/D conversion the digital data is stored in the hard disk of the PC and subsequently in floppies. Standard interface are amicable for controlling digital instrument and transferring data to the PC. We have used general purpose interface bus (GPIB) for this purpose . The bus protocol was evolved by Hewlett - Packard company (USA) under the name of HP-IB for the interconnection of instruments . The GP IB interface card provides a low cost interconnection for up to 15 digital instruments over a distance (about 20 mts). The GPIB consists of 16 lines of which 8 are meant for parallel data transfer and 8 form the command channels. The maximum data transfer rate is about 1 MByte / sec, but transfer rates achieved in PC based instrument is about 250 MByte/sec . A GPIB cable is terminated at both ends by identical connectors which permit Piggy - back connections .

In the present work, a GPIB interface incorporated with HP digital storage oscilloscope is used for transferring of data from the oscilloscope memory to computer. For IBM-PC and a compatible GPIB interface called GPIB-PC2 is used. It is possible to use this software through user programs written in FORTRAN and PASCAL. Commands for sending data from the HP oscilloscope to PC-XT using the IBIC menu are given below :

```
        IBIC
1       IBFIND   Osc
2       IBWRT ":ACQUIRE:TYPE NORMAL;COUNT 1;POINTS 512"
3       IBWRT ":DIGITIZE CHANNEL 1"
4       IBWRT ":SYSTEM:HEADER OFF;:EOI ON"
5       IBWRT ":WAVEFORM:SOURCE CHANNEL1;FORMAT ASCII"
6       IBWRT ":WAVEFORM:DATA?"
7       IBRDF          OUTPUT
        IBCLR
        IBLOC
        QUIT
```

The first command is to open the oscilloscope. The second command is the acquire subsystem. Third and fourth are for counting 512 data and its digitization . Command six for format for source and output . Seventh command brings the oscilloscope in action to get ready to transfer data. The next command stores the data in PC under the file name OUTPUT.

APPENDIX - C

C 1 FAST FOURIER TRANSFORMATION

Fast fourier transform is a very efficient algorithm which calculates the discrete fourier transform (DFT) based on discrete version of the fourier integral pair. From this it is possible to make rapid transformations between time and frequency domains.

The DFT is a finite sequences { Xr }, r = 0,1,2,3,........,(N-1) is a new finite sequence { Xk } defined as,

$$X_k = \frac{1}{N} \sum_{r=0}^{N-1} X_r \, e^{-\imath\{2\pi K_r / N\}} \qquad K_r = 0,1,2.......,(N-1)$$

If we are working out values of X_k by a direct approach we will have to make N multiplications of the form { X_r } $\times$ $\{e^{-\imath(2\pi K_r/N)}\}$ for each of N values of X_k and so the total work of calculating the full sequence X_k would require N^2 multiplications. The FFT reduces this work to a number of operations of the order $N\text{Log}_2 N$. The FFT therefore offers an enormous reduction in computer processing time and also increases accuracy.

The signal to be analyzed is initially in analog form and is (i) sampled (ii) digitized (iii) stored in the computer memory and (iv) spectral analysis is carried out using fast fourier transforms (FFT).

C 2 SPECTRAL ANALYSIS

Spectra provide a frequency-domain resolution of physical quantities such as displacement, velocity, acceleration and force. Spectral data can be processed in such a same manner as time domain data in determining correlation functions. There are two classes for spectral data :

(i) CROSS-SPECTRUM

The cross spectrum measure the similarity between two signals in frequency domain, it is the fourier transform of the cross-correlation and expresses the similarity as a function of frequency. Conjugate multiplication is applied to calculate the cross spectral density function.

(ii) AUTO-SPECTRUM (POWER -SPECTRUM)

It is a similar measurement in frequency domain, the measured quantity being multiplied by itself such that

the coefficients of the components are expressed as the square of their magnitude.

An electrical analogy by Betts considers a periodic function F(t) which defines either voltage or current variation associated with a circuit in which the power is dissipated by a one-ohm resistor. This would be regarded as normalized power (based on unit resistance) and thus the average value is given by :

$$P = \frac{1}{T} \int_{-T/2}^{+T/2} f^2(t)\, dt$$

In terms of the fourier transform this can be rewritten as,

$$P = \frac{1}{T} \int_{-T/2}^{+T/2} f(t)\, dt \int_{-T/2}^{+T/2} F(j\omega)\, \exp(j\omega t)\, df$$

$$P = \frac{1}{T} \int_{-T/2}^{+T/2} |F(j\omega)|^2\, df$$

Since Hz = (1/time) = (1/sec), the integral reduces to (watts/Hz).

An alternative but complementary way of describing the power spectrum is as follows, physically this is simply a

measure of how much energy is contained within the signal in each frequency band. If $\hat{X}(t,\omega,\Delta\omega)$ is that part of the signal $X(t)$ which lies in the frequency band $\Delta\omega$ center at frequency ω. Then the mean square value within this band is

$$S^2(\omega) = \lim_{T\to\infty}\left(\frac{1}{T}\int_0^T \hat{X}^2(t,\omega,\Delta\omega)\,dt\right)$$

Then power spectral density can be defined as

$$|F(\omega)|^2 = \lim_{f\to\infty}\left[S^2(\omega)/(\omega\,\bar{x})\right]$$

where $\bar{x}^2$ is the mean square (or variance σ^2) of the original signal $X(t)$.

```
C         PROGRAM FOR SCALING THE SIGNAL DATA

          integer*4 a
          dimension a(1024),b(1024)
          integer*4 amax,amin
          open(unit=12,file='s.in',status='old')
          read(12,*)(a(i),i=1,512)
          close(unit=12,status='keep')
          amax=0
          amin=1000000
          do 10 i=1,512
          amax=max0(amax,a(i))
          amin=min0(amin,a(i))
  10      continue
          print*,amax,amin
          do 20 i=1,512
          c=256*(a(i)-amin)
          b(i)=c/(amax-amin)
  20      continue
          do 30 i=1,512
          a(i)=b(i)
  30      continue
          open(unit=20,file='integ.dat',status='unknown')
          write(20,*)(a(i),i=1,512)
          close(unit=20,status='keep')
          stop
          end
```

```
      PROGRAM ELASTIC

C     CALCULATION OF FREQUENCY SPECTRUM  OF DIGITIZED
C     SIGNALS USING FFT FOR ELASTIC GATE.

      dimension a(3200),power(3200),auto(3200),alag(3200)
      dimension b(3200),a2(3200)
      complex x(3200)
      common / tr /troom

      print *, 'what are nu ndata del '
      read *, nu,ndata,del

      n=2**nu
      del=10.0*del/1024
      fmax=1.0/del
      tt=del*(n-1)
      pi=3.1415926

      scale=1.0

      open(unit=21,file='integ.dat',status='old')
      read(21,*) (a(i),i=1,ndata)
      close(unit=21,status='keep')

      print *, 'signal data has been read'

c     remove  stray mean.

      call trap(a,ndata,e)
      do 65 i=1,ndata
      a(i)=a(i)-e
65    continue

c     filter data (Tukey- Hanning formula).

      tt1=0.5*del*(ndata-1)
      do 75 i=1,ndata
      t1=del*(i-1)
      wt=0.5*(1.0+cos(pi*(t1-tt1)/tt1))
      a2(i)=a(i)**2
      a(i)=a(i)*wt*scale
75    continue

      call trap(a2,ndata,variance)

      do 45 i=ndata+1,n
      a(i)=0.0
45    continue
```

```
      call fftr(a,b,x,nu,del)

      do 100 i=1,n
      r=real(x(i))
      s=imag(x(i))
      power(i)=sqrt(r**2+s**2)
 100  continue
      print *, 'frequency spectrum calculated'


      power1 =-1.0 E+06
      Do 111 i=1,n
      power1 =max0(ifix(power1),ifix(power(i)))


111   continue
      do  116 i=1,n
      power(i)=power(i)/power1
116   continue

      nd2=n/2
      fnyq=0.5*fmax


      open(unit=24,file='freq.dat',status='unknown')
      write(24,1230)
1230  format(/2x,'freq in Hz.; amplitude dimensionless',//)
c      write(24,1200)
1200  format(6x,'freq',7x,'amplitude (real, imaginary mod)',//)
      write(24,1250) (b(i),power(i),i=1,nd2)
1250  format(2x,e12.5,4x,e12.5)
c      write(24,1275) fnyq
1275  format(/5x,'Nyquist frequency (Hz) ',e12.5)
      close(unit=24,status='keep')

      stop
      end

      subroutine fftr(a,b,x,nu,del)
      dimension  x(3200),b(3200),a(3200)
      complex x,u,w,t
      n=2**nu
      pi=3.141592653
      tt=(n-1)*del

      do 5 jj=1,n
      b(jj) = (jj-1)/tt
5     continue

      do 6 i=1,n
      x(i)=cmplx(a(i),0.0)
6     continue

      do 20 l=1,nu
      le=2**(nu+1-l)
      le1=le/2
      u=(1.,0.)
      w=cmplx(cos(pi/float(le1)),-sin(pi/float(le1)))
```

```
      do 20 j=1,le1

      do 10 i=j,n,le
      ip=i+le1
      t=x(i)+x(ip)
      x(ip)=(x(i)-x(ip))*u
10    x(i)=t
20    u=u*w

      nv2=n/2
      nm1=n-1
      j=1
      do 30 i=1,nm1
      if(i.ge.j)go to 25
      t=x(j)
      x(j)=x(i)
      x(i)=t
25    k=nv2
35    if(k.ge.j)go to 30
      j=j-k
      k=k/2
      go to 35


30    j=j+k

      return
      end

      subroutine simpson (x,n,e)
      dimension x(3200)
      fx=0.0
      do 5 i=2,n-1,2
5     fx=fx+x(i)
      fy=0.0
      do 10 i=3,n-2,2
10    fy=fy+x(i)
      e=(x(1)+x(n)+4.0*fx+2.0*fy)/(3.0*(n-1))
      return
      end

      subroutine trap(x,n,e)
      dimension x(3200)

      fx=0.0
      do 10 i=2,n-1
      fx=fx+x(i)
10    continue

      e=(x(1)+x(n)+2.0*fx)/(2.0*(n-1))

      return
      end
```

```
      PROGRAM RIGID

C     CALCULATION OF FREQUENCY SPECTRUM  OF DIGITIZED
C     SIGNALS USING FFT FOR RIGID GATE.

      dimension acc(1200),power(1200),auto(1200),alag(1200)
      dimension b(1200),a2(1200),force(1200)
      complex accf(1200),forcef(1200)

      print *, 'what is the mass of the gate in kg'
      print *, '  '
      read *, am
      print *, ' '
      print *, 'give the force and acceleration scale factors'
      print *, 'in units of N/mv and m/s*s*mv'
      print *, '  '
      read *, sfr,sac
      print *, ' '
      print *, 'give the oscilloscope voltage scales for the force'
      print *, 'and acceleration signals in mv/division'
      print *, ' '
      read *, scala,scalf
      print *, ' '
      print *, 'IMPORTANT: THE TIME SCALES ON THE OSCILLOSCOPE FOR'
      print *, 'THE TWO SIGNALS MUST BE EQUAL (IN SECONDS)'
      print *, 'what is the time scale used on the oscilloscope'
      print *, ' '
      read *, del

      nu=9
      n=2**nu
      ndata=n
      del=10.0*del/n
      fmax=1.0/del
      tt=del*(n-1)
      pi=3.141592653

      open(unit=21,file='acc.dat',status='old')
      read(21,*) (acc(i),i=1,ndata)
      close(unit=21,status='keep')

      open(unit=22,file='force.dat',status='old')
      read(22,*) (force(i),i=1,ndata)
      close(unit=22,status='keep')

      print *, 'signal data has been read'

c     filter data (Tukey- Hanning formula).

      tt1=0.5*del*(ndata-1)
      do 75 i=1,ndata
      t1=del*(i-1)
      wt=0.5*(1.0+cos(pi*(t1-tt1)/tt1))
      acc(i)=8.0*(acc(i)/32640)*wt*scala*sac*am
      force(i)=8.0*(force(i)/32640)*wt*scalf*sfr
75    continue
```

```
c       remove stray mean.

        call trap(acc,ndata,ea)
        call trap(force,ndata,ef)
        do 65 i=1,ndata
        acc(i)=acc(i)-ea
        force(i)=force(i)-ef
65      continue

c       add zeroes to complete string.

        do 45 i=ndata+1,n
        acc(i)=0.0
        force(i)=0.0
45      continue

        call fftr(acc,b,accf,nu,del)
        call fftr(force,b,forcef,nu,del)

        do 100 i=1,n
        r=real(accf(i)-forcef(i))
        s=imag(accf(i)-forcef(i))
        power(i)=sqrt(r**2+s**2)
100     continue
        print *, 'frequency spectrum of fluid force calculated'

        power1 = -1.0 E+06
        Do 226 i =1,n
        power1 = max0(ifix(power1),ifix(power(i)))
226     continue
        do  116 i=1,n
        power(i)=(power(i))/(power1)
116     continue

        nd2=n/2
        fnyq=0.5*fmax

        open(unit=24,file='freq.dat',status='unknown')
        write(24,1230)
1230    format(/2x,'freq in Hz.; amplitude dimensionless',//)
        write(24,1200)
1200    format(6x,'freq',7x,'amplitude (real, imaginary mod)',//
        write(24,1250) (b(i),power(i),i=1,nd2)
1250    format(2x,e12.5,4x,e12.5)
        write(24,1275) fnyq
1275    format(/5x,'Nyquist frequency (Hz) ',e12.5)
        close(unit=24,status='keep')

        stop
        end

        subroutine fftr(a,b,x,nu,del)
        dimension  x(1200),b(1200),a(1200)
        complex x,u,w,t

        n=2**nu
        pi=3.141592653
```

```
        do 5 jj=1,n
        b(jj) = (jj-1)/tt
5       continue

        do 6 i=1,n
        x(i)=cmplx(a(i),0.0)
6       continue

        do 20 l=1,nu
        le=2**(nu+1-l)
        le1=le/2
        u=(1.,0.)
        w=cmplx(cos(pi/float(le1)),-sin(pi/float(le1)))

        do 20 j=1,le1




        do 10 i=j,n,le
        ip=i+le1
        t=x(i)+x(ip)
        x(ip)=(x(i)-x(ip))*u
10      x(i)=t
20      u=u*w

        nv2=n/2
        nm1=n-1
        j=1
        do 30 i=1,nm1
        if(i.ge.j)go to 25
        t=x(j)
        x(j)=x(i)
        x(i)=t
25      k=nv2
35      if(k.ge.j)go to 30
        j=j-k
        k=k/2
        go to 35
30      j=j+k

        return
        end
```

```
      subroutine simpson (x,n,e)
      dimension x(1200)
      fx=0.0
      do 5 i=2,n-1,2
5     fx=fx+x(i)
      fy=0.0
      do 10 i=3,n-2,2
10    fy=fy+x(i)
      e=(x(1)+x(n)+4.0*fx+2.0*fy)/(3.0*(n-1))
      return
      end

      subroutine trap(x,n,e)
      dimension x(1200)

      fx=0.0
      do 10 i=2,n-1
      fx=fx+x(i)
10    continue

      e=(x(1)+x(n)+2.0*fx)/(2.0*(n-1))

      return
      end
```

```fortran
      PROGRAM PHASE

C     CALCULATION OF PHASE ANGLE BETWEEN THE FLUID FORCE
C     AND THE GATE DISPLACEMENT.


      dimension acc(1200),power(1200),auto(1200),alag(1200)
      dimension b(1200),a2(1200),force(1200),disp(1200)
      complex accf(1200),forcef(1200),dispf(1200)

      print *, 'what is the mass of the gate in kg'
      print *, '  '
      read *, am

      print *, ' '
      print *, 'give the force and acceleration scale factors'
      print *, 'in units of N/mv and m/s*s*mv'
      print *, '  '
      read *, sfr,sac
      print *, ' '
      print *, 'give the oscilloscope voltage scales for the force'
      print *, 'and acceleration signals in mv/division'
      print *, ' '
      read *, scala,scalf
      print *, ' '
      print *, 'IMPORTANT: THE TIME SCALES ON THE OSCILLOSCOPE FOR'
      print *, 'THE THREE SIGNALS MUST BE EQUAL'
      print *, 'what is the time scale used on the oscilloscope'
      print *, ' '
      read *, del

      nu=9
      n=2**nu
      ndata=n
      del=10.0*del/n
      fmax=1.0/del
      tt=del*(n-1)
      pi=3.141592653

      open(unit=21,file='acc.dat',status='old')
      read(21,*) (acc(i),i=1,ndata)
      close(unit=21,status='keep')

      open(unit=22,file='force.dat',status='old')
      read(22,*) (force(i),i=1,ndata)
      close(unit=22,status='keep')

      open(unit=23,file='disp.dat',status='old')
      read(23,*) (disp(i),i=1,ndata)
      close(unit=23,status='keep')
```

```
      print *, 'signal data has been read'

c     filter data (Tukey- Hanning formula).

      tt1=0.5*del*(ndata-1)
      do 75 i=1,ndata
      t1=del*(i-1)
      wt=0.5*(1.0+cos(pi*(t1-tt1)/tt1))
      acc(i)=8.0*(acc(i)/32640)*wt*scala*sac*am
      force(i)=8.0*(force(i)/32640)*wt*scalf*sfr
      disp(i)=8.0*(disp(i)/32640)*wt*scalf*sfr
75    continue

c     remove stray mean.

      call trap(acc,ndata,ea)
      call trap(force,ndata,ef)
      call trap(disp,ndata,ed)
      do 65 i=1,ndata
      acc(i)=acc(i)-ea
      force(i)=force(i)-ef
      disp(i)=disp(i)-ed
65    continue

c     add zeroes to complete string.

      do 45 i=ndata+1,n
      acc(i)=0.0
      force(i)=0.0
      disp(i)=0.0
45    continue

      call fftr(acc,b,accf,nu,del)
      call fftr(force,b,forcef,nu,del)
      call fftr(disp,b,dispf,nu,del)

      do 100 i=1,n

      r=real(accf(i)-forcef(i))
      s=imag(accf(i)-forcef(i))
      power(i)=sqrt(r**2+s**2)

      rd=real(dispf(i))
      sd=imag(dispf(i))

      p1=atan(r/s)
      p2=atan(rd/sd)

      alag(i)=abs(p1-p2)
```

```
100     continue
        print *, 'frequency spectrum of fluid force calculated'
        print *, ' '
        print *, 'phase angle between fluid force and gate'
        print *, 'displacement calculated'

        power1=power(1)
        do  116 i=1,n
        power(i)=power(i)/power1
116     continue

        nd2=n/2
        fnyq=0.5*fmax

        open(unit=24,file='freq.dat',status='unknown')
        write(24,1230)
1230    format(/2x,'freq in Hz.; amplitude dimensionless',//)
        write(24,1200)
1200    format(6x,'freq',7x,'amplitude',8x,'phase angle',//)
        write(24,1250) (b(i),power(i),alag(i),i=1,nd2)
1250    format(2x,e12.5,4x,e12.5,4x,e12.5)
        write(24,1275) fnyq
1275    format(/5x,'Nyquist frequency (Hz) ',e12.5)
        close(unit=24,status='keep')

        stop
        end

        subroutine fftr(a,b,x,nu,del)
        dimension  x(1200),b(1200),a(1200)
        complex x,u,w,t


        n=2**nu
        pi=3.141592653
        tt=(n-1)*del

        do 5 jj=1,n
        b(jj) = (jj-1)/tt
5       continue

        do 6 i=1,n
        x(i)=cmplx(a(i),0.0)
6       continue

        do 20 l=1,nu
        le=2**(nu+1-l)
        le1=le/2
        u=(1.,0.)
        w=cmplx(cos(pi/float(le1)),-sin(pi/float(le1)))
```

```
      do 20 j=1,le1

      do 10 i=j,n,le
      ip=i+le1
      t=x(i)+x(ip)
      x(ip)=(x(i)-x(ip))*u
10    x(i)=t
20    u=u*w

      nv2=n/2
      nm1=n-1
      j=1
      do 30 i=1,nm1
      if(i.ge.j)go to 25
      t=x(j)
      x(j)=x(i)
      x(i)=t
25    k=nv2
35    if(k.ge.j)go to 30
      j=j-k
      k=k/2
      go to 35
30    j=j+k

      return
      end

      subroutine simpson (x,n,e)
      dimension x(1200)
      fx=0.0
      do 5 i=2,n-1,2
5     fx=fx+x(i)
      fy=0.0
      do 10 i=3,n-2,2
10    fy=fy+x(i)
      e=(x(1)+x(n)+4.0*fx+2.0*fy)/(3.0*(n-1))
      return
      end

      subroutine trap(x,n,e)
      dimension x(1200)

      fx=0.0
      do 10 i=2,n-1
      fx=fx+x(i)
10    continue

      e=(x(1)+x(n)+2.0*fx)/(2.0*(n-1))

      return
      end
```